1989

PROCEEDINGS

WORKSHOP ON "THE SEISMIC RISK IN THE SAN DIEGO REGION: SPECIAL FOCUS ON THE ROSE CANYON FAULT SYSTEM"

June 29-30, 1989

Reuben H. Fleet Space Theater, Grayson Boehm Lecture Hall
Balboa Park, San Diego, California

Editorial Committee

Editor: Glenn Roquemore, University of California, Irvine
Associate Editor: Susan Tanges, Leighton and Associates
Project Manager: Marian Wright, Southern California Earthquake Preparedness Project

Michael Reichle, California Division of Mines and Geology; Thomas Heaton, U.S. Geological Survey; Diane Murbach, Geopacifica; Gilbert Najera, Southern California Earthquake Preparedness Project

Word Processor: Patricia Johnson, Southern California Earthquake Preparedness Project

Cover Image Courtesy of SPOT Image Corporation,
Reston, Virginia, Copyright CNES 1989
Provided by Ronald Blom and Steven Adams, JPL, Pasadena, CA

also included

San Diego Association of Geologists' Field Trip Road Log

"Fault Features Between La Jolla, U.S.A. and Ensenada, Mexico"

October 21-22, 1989

DETAILED GRAVITY STUDIES AND THE TECTONICS OF THE ROSE CANYON--POINT LOMA--LA NACION FAULT SYSTEM, SAN DIEGO, CALIFORNIA

Monte Marshall

Department of Geological Sciences
San Diego State University
San Diego, California

ABSTRACT

Detailed gravity traverses, in conjunction with regional gravity and basement topography maps, support the suggestion that the San Diego basin is a nested graben in a zone of tension between two offset strands of the Rose Canyon fault. Centered near the south end of Silver Strand, the basin is about 6,000 feet deep and 12 miles wide. The graben is bounded on the east by strands of the La Nacion fault zone. At the south end of San Diego Bay much of the dip-slip occurred on faults which are centered two miles west of most of the mapped traces of the La Nacion fault. Eight miles to the north, downtown San Diego overlies the graben axis at a depth of about 4000 feet. Here the east flank of the graben is formed largely by several strands of the La Nacion fault zone between Euclid and 60th that have a net throw of several thousand feet. West of downtown San Diego, the gravity data suggest that the main fault zone forming the western flank of the graben lies east of the mapped traces of the Pt. Loma fault and probably underlies Loma Portal and the Naval Training Center and extends south into the harbor between Pt. Loma and the Spanish Bight fault zone. The graben is asymmetric and has much less relief two miles to the north of downtown San Diego. Except for several thousand feet of down-to-the-east throw on the Pt. Loma fault zone, the 30th St.--Texas St. and La Nacion faults have only 500 to 1000 feet of throw. A graben centered on Hwy. 163 between Mission Hills and Texas St. is the shallow northward extension of the axis of the San Diego graben. The cross-section is made asymmetric by the northward translation along the Rose Canyon fault of a deeper, higher relief portion of the basin. The Rose Canyon fault has 500 to 1000 feet of down-to-the-west throw, a sense that continues to Rose Canyon. The Pt. Loma fault zone is not seen north of San Diego River, and Mission Bay appears to be an asymmetric basin formed by a gently east-sloping basement beneath the bay terminated by a basement high along the Rose Canyon fault. The sense of throw along the Rose Canyon fault changes in Rose Canyon. At Mt. Soledad the gravity data indicate several thousand feet of up-to-the-southwest throw on the Rose Canyon fault, which is probably thrust-slip on faults dipping southwesterly beneath the mountain. Some of the throw is also accommodated on a fault strand about 2000 feet north of the main trace of the Rose Canyon fault and on the Muirlands fault.

These basement structures inferred from the gravity data can be generally explained by curves in a strike-slip fault. The basement high at Mt. Soledad is due to a restraining (compression) bend in the Rose Canyon fault. The shallow basin beneath Mission Bay and, much more significantly, the nested graben under San Diego Bay result from a releasing (extension) bend of the Rose Canyon fault, making the graben a rhombochasm. The proposed rhombochasm trends about N10W, is centered beneath south San Diego Bay, is about 12 miles wide, and extends from downtown San Diego to several miles south of the U.S.--Mexico border. The strike-slip faulting possibly continues on a NW-SE trending fault that joins the San Miguel fault zone 30 km to the southeast.

The transformation of the predominantly strike-slip Rose Canyon fault into the N-S trending, predominantly dip-slip La Nacion--Pt. Loma fault zones explains why the Rose Canyon seems to disappear south of Mission Hills. The genetic and geometric connection between these fault zones makes them both either active or inactive, in that strike-slip on the Rose Canyon fault zone inevitably leads to dip-slip on the Pt. Loma--La Nacion fault zones, and vice-versa. The cluster of earthquake epicenters in south San Diego Bay suggests that, at least over the short-term, the faults at the center of the graben are the most active. Whether over the long-term this fault system is characterized by numerous, small earthquakes in the graben and fewer, larger earthquakes on the adjacent strike-slip faults, like the Rose Canyon, needs to be studied. Assuming that the San Diego graben is a simple rhombochasm, the long-term slip rate on the Rose Canyon fault can be estimated using sediment thickness and age in the rhombochasm. Four kilometers of post-Miocene strike-slip is calculated assuming a thickness of one kilometer of Plio-Pleistocene sediments and an average fault-dip of 45 degrees. Another calculation, based on the amount of ductile crustal extension needed to produce the crustal thinning that forms the basin, yields two kilometers of post-Miocene strike-slip. This estimate assumes a 20 km-thick, ductily stretched zone in the middle and lower crust. Assuming a net-slip of 3 km in the past 6 million years, the long-term, strike-slip rate on the Rose Canyon fault is a moderately high 0.5 mm per year. This is slower than a 1 to 2 mm per year, post-Pliocene rate estimated on purely geologic observations. The similarity of the two values is interesting and perhaps significant, but the accuracy of these calculated slip rates depends on the validity of the rhombochasm model and on several geologic assumptions. A long-term, dip-slip rate of 0.2 mm/Y is calculated for the Pt. Loma--La Nacion fault zones, assuming an average fault dip of 45 degrees. The strike-slip rate on the Rose Canyon fault is about three times the dip-slip rate on the Pt. Loma--La Nacion fault zones. Because of the small angle between the Rose Canyon and the basin-bounding faults, the Pt. Loma--La Nacion fault zone is probably characterized by a component of strike-slip. For fault dips of 60 to 30 degrees, the calculated net-slip direction ranges from predominantly dip-slip to predominantly strike-slip, respectively.

INTRODUCTION

In an earlier paper, detailed gravity profiles across the La Nacion fault zone were shown to be useful in locating major fault strands and estimating the sense and approximate amount of their throw (Marshall, 1979). This paper shows the westerly extension of these profiles across the north end of San Diego harbor and across the Rose Canyon fault zone north to La Jolla. These profiles, in conjunction with the regional gravity data and basement topography of Elliott (1970), can be used to infer a fairly detailed structure of the basement in the vicinity of the La Nacion, Pt. Loma, and Rose Canyon fault zones between the south end of San Diego Bay and Mt. Soledad in La Jolla.

In the second part of this paper the crustal cross-sections suggested by the gravity data will be fit into a tectonic model that proposes that both the Rose Canyon and Pt. Loma--La Nacion fault zones are part of the same fault system. Several of the consequences of this model are examined, including an estimate of the long-term slip rate on the Rose Canyon fault.

THE GRAVITY PROFILES

The twelve gravity profiles presented here are the combined results of nineteen SDSU senior theses. The profiles are mostly east-west, range from 2 to 10 miles long, and extend from south San Diego Bay to La Jolla (Fig.1). The average station spacing is about 500 feet. The values shown are Bouguer anomalies, i.e., they are the difference between the measured gravity at each station and the theoretic value (using the GRS67 formula). Terrain corrections were made when needed. The observed gravity values are based on the California base station network (Chapman, 1966) and updated by the IGSN71 revised values (Oliver, 1980). A density of 2.3 gm/cc was used in the elevation and terrain corrections since the surface rocks are all sedimentary. A possible regional eastward gradient of about -1 to -2 two mgals per mile has not been removed. The original profiles were all plotted on the scale of 7.5 min. quads (1:24,000). The detailed profiles presented here are interpreted in the regional context of the Bouguer anomaly and basement contour maps of Elliott (1970 ; Figs. 2 and 3, this paper). For comparison all the profiles are also printed to the same scale as that of the fault map of Kennedy, 1975 (see Plate 1).

The way in which S-shaped steps in gravity profiles suggest the location, relief, or throw, and the depth of a faulted sediment-basement contact is discussed in geophysical texts and in Marshall, 1979. As with interpreting all geophysical data, certain precautions must be kept in mind. The most pertinent here are: (1) strictly speaking, a step in the gravity profile shows only the existence of a subsurface density change. Whether this density contrast is due to facies changes, e.g., a conglomerate-filled channel, a buttress unconformity, or is due to faulting of high density rocks against lower density rocks or sediments is ambiguous. (2) The use of the amplitude of the gravity steps to estimate throw, T, on faults depends on the magnitude of the density contrast across the fault. The formula is T = anomaly amplitude /(0.013 times the density contrast). Thus a 6 mgal step would indicate a throw of about 800 ft. in an area where the density contrast is 0.6 gm/cc, e.g., low density sediments (density 2.2 gm/cc) faulted against metavolcanic basement (density 2.8 gm/cc). However, if the same 6 mgal step were due to a density contrast of 0.3 gm/cc, e.g., 2.2 gm/cc sediments faulted against conglomerates with a density of 2.5 gm/cc, the throw required would be 1600 ft. The accuracy of the estimated throw across a fault depends on the accuracy of the estimated weighted mean density contrast across it. An average density contrast of 0.3 gm/cc is used in this study. It is the value which, if used the earlier study of the La Nacion fault zone (Marshall, 1979), gives the best agreement between the calculated throws and the differences in elevation predicted by Elliott's (1970) basement contour map. (3) The steepness or gradient of the gravity steps decreases with increasing depth to the density contrast. A near-surface step in the basement with 200 ft. of relief produces a well defined, short wavelength anomaly, whereas it would produce a long wavelength, gently sloping curve if at a depth of 3500 feet (Fig. 4). There is no well-defined midpoint on the gravity step to determine the fault location in this case. The accurate location of faults in a deep basin depends on their having measurable density contrasts in the near-surface sediments.

The relation between the gravity profiles and the local structure will be discussed in a south to north sequence.

South San Diego Bay

The Palm Ave.--Main St.--Otay Rd. profiles span the eastern flank of the center of the -35 mgal anomaly and corresponding 6,000 foot deep structural basin shown by Elliott (Figs. 2 and 3). Unlike the profiles to the north there are few steps corresponding to mapped fault traces of the La Nacion fault (Fig.5). The midpoint of the fairly smooth 20 mgal decrease suggests that the geometric center of faulting is approximately one half mile east of 3rd St. The only faults mapped in this area are the southward extension, on photographic evidence, of the Sweetwater fault

(Kennedy et al., 1975). Most of the well-mapped strands of Kennedy et al. (1975) lie to the east of I-805, where the gravity data show little throw. The smoothness of the slope between 3rd. Ave. and I-805 probably results from the depth to basement of 3000 to 4000 feet and a lack of near-surface density contrasts. Whether the basin is due to large displacement on a few strands, such as the two faults mapped on the basis of photographic evidence, or to many, closely spaced strands with lesser displacement is unknown. At the west end of the profile there are small steps in the gravity curves in the vicinity of I-5. The peculiar, down-up-down curve on the Palm Ave. line is the shape expected from an offset high density layer, such as a conglomerate, sandwiched between lower density layers. It coincides with a mapped fault, which, if extrapolated to the north, intersects the Main St. profile near I-5 (Kennedy et al., 1975). These small steps and down-up-down curves show that near-surface density contrasts can reveal a fault even when the basement is 5,000 ft. deep.

Metropolitan San Diego

This profile from the La Nacion fault zone on the east to the beginning of the series of up-to-the-west faults that bound the Pt. Loma block shows well the nested graben of the San Diego basin (Fig. 6). Judging by the steps in the gravity profile, the strands of the La Nacion fault zone which have accommodated most of the throw are the two that cross Imperial Ave. about 1000 feet east of Euclid and 1500 feet west of 60th St.

At the western end of the profile the gravity begins increasing rapidly--from -20 mgals at the Harbor Island overpass to only -8 mgals two miles to the west in the vicinity of Rosecrans Blvd. (Fig.2; Biehler, 1982). Such a steep gradient indicates several thousand feet of uplift on the fault zone forming the western edge of the basin in this area. This large, up-to-the-west offset is opposite to that shown by Kennedy on his Pt. Loma fault cross-section (Kennedy and Peterson, 1975). The gravity data show that the basement beneath San Diego Harbor here is faulted down and not up. Assuming his map showing outcrops of the Cretaceous Cabrillo sandstone to the east of his trace of the Pt. Loma fault along Nimitz Blvd. is correct, the major fault zone that has uplifted the Pt. Loma block probably extends from Loma Portal south thru the Naval Training Center into the harbor west of the Spanish Bight fault zone. Extending the gravity lines west to the ocean will hopefully yield more precise information on the location and nature of this zone that forms the western boundary of the graben. (See the article in the fieldtrip guidebook in this volume for a more complete discussion of the the implications of the gravity data on the location and nature of the western graben faults.) Near the western end of the profile there are two gravity-indicated faults, with up-to-the-west throws near the Harbor Island overpass. At the east end of Harbor

Drive, however, the two strands of the Spanish Bight fault mapped by Kennedy and Welday (1980) that should cross it to the east of the overpass are not seen on the gravity profile.

The three lines in downtown San Diego show that it lies on the axis and near the north end of the San Diego basin where the depth to basement is estimated at 3000 to 4000 feet (Figs. 2 & 3). The profiles are fairly featureless from the harbor east to about 12th St. (Fig. 7). A step in the gravity suggests a NNW trending fault, down-to-the-east, between Kettner and Pacific Coast Highway on Broadway and several hundred feet east of Kettner on Market. This could be a strand of the Spanish Bight--Coronado fault zones of Kennedy and Welday (1980). Further uptown there seems to be little correlation in the anomalies between the three lines, except that they begin near 12th St. and decrease in amplitude toward the south. When examined in detail there is also little correlation between the gravity variations and the extrapolation of the two main fault zones in this area--the southern ends of the Rose Canyon and Florida Canyon faults (Fig.7). The prominent anomaly at 12th and Broadway coincides exactly with Kern's (1989) extension of the Rose Canyon fault into this area. However, if the fault does continue further southeast into downtown San Diego it apparently loses its up-to- the-east throw seen for many miles to the north. The Florida Canyon fault likewise is seen on only one profile--the intermediate Market St. line. Even here the sharp down-to-the-east step is based on only one data point. Since the downtown is probably close to the juncture of the predominantly strike-slip Rose Canyon fault zone and predominantly dip-slip La Nacion fault zone, the structure could well be complicated here. Hopefully future surveys using a more sensitive gravity meter and more careful elevation control will find the shallow, fault-related density contrasts needed to locate and decipher the fault pattern in downtown San Diego.

Barnett - University Avenue

Several miles to the north of the metropolitan San Diego profile, this gravity profile shows that the graben is asymmetric (Fig. 8). The throw on the relatively narrow Pt. Loma fault zone is two to three thousand feet, whereas the uplift on the eastern flank is caused by 500 to 1000 feet of throw on faults spaced several miles apart. The basement shallows from about 3000 feet deep near I-5 to about 1000 feet at the east end of the traverse, and the nested graben of the San Diego basin ends several miles to the north (Figs. 2 and 3). The Rose Canyon fault has 500 to 1000 feet of throw where it crosses Washington near I-5. The sense of throw, down-to-the-west, remains the same northward to Rose Canyon. The basement high between the Rose Canyon fault and Hwy. 163 is probably not a true horst since the the basement low to the west of the fault is likely due to the strike-slip juxtaposition of a deeper part of the basin from the south. The basement low between Mission Hills and 30th St. probably is a graben and lies on the northward extension of the San Diego basin axis seen on the metropolitan San Diego profile to the south. The down-to-the-west displacement on a possible fault near 30th St. (as well as on a profile one half mile to the south) shifts over to the Texas St. fault on profiles to the north. Such echelon stepping is seen in the La Nacion fault zone further to the south (Marshall, 1979). Several preliminary gravity studies along and to the north of Friars Road show that the basement high beneath Mission Hills and the low centered near Highway 163 continues northward for several miles (Taylor, 1983; Brigandi, 1982). This basement relief coincides with the anticline-syncline pair mapped by Kennedy et al.(1975) on south Linda Vista mesa. Since the western edge of the basement high is the Rose Canyon fault and the eastern edge of the syncline is near the Texas St. fault, the inflection point between them could be fault controlled. The gravity data shows that this possible fault trends north-south, is about 1.5 miles east of the Rose Canyon fault on south Linda Vista Mesa, and would intersect Washington near Goldfinch, where the gravity data suggest a fault. Its extension south of Washington coincides with the N-S canyon of Reynard Way, and raises the possibility that the canyon is fault-controlled.

San Diego River - Mission Valley

This profile extends from the mouth of Mission Valley to the west end of the middle jetty (Fig. 9). Only one mile north of the Barnett--University profile, it shows the nature of the Rose Canyon fault at its east end and the Pt. Loma fault zone on the west. The down-to-west throw on the Rose Canyon fault is about 1000 feet. The up-to-the-west displacement on the Pt. Loma fault zone is considerably less than that to the south. The increase in gravity from the low adjacent to the Rose Canyon fault to the ocean is 7 mgals whereas it is 16 mgals in the Barnett traverse (See the shoreline value in Fig. 2). The two mgal/mile gradient corresponds to an easterly slope on the basement of five degrees, a dip value typical of the sedimentary rocks exposed to the south of the jetty (Kennedy and Peterson, 1975). The one step in the profile corresponds to Kennedy's Pt. Loma fault, but, as was the case to the south, the gravity suggests the overall throw on the fault zone is up-to-the-west and not up-to-the-east as shown in the cross-section of Kennedy and Peterson (1975).

South Mission Bay - Tecolote Canyon

A mile further north, the flatness of the gravity profile across the bay suggests the end of the Pt. Loma fault zone (Fig. 10). The throw on the Rose Canyon fault is less than 1000 feet and the decrease in the gradient across the zone shows that it is broader here than on adjacent traverses, in agreement with the mapping of Kern (1989). The decrease in the gravity at the extreme east end of this profile is the beginning of a 6 mgal decrease that reflects the eastern margin of the basement ridge paralleling the Rose Canyon fault in this area discussed earlier.

North Mission Bay

Several miles further north, the throw on the Rose Canyon fault near Clairmont Dr. increases to a local maximum of about 1500 feet (Fig. 11). The gravity gradient across the bay also steepens, corresponding to an easterly dip on the basement of about five degrees. A local gravity minimum suggests a small basin at the northeast end of the bay (Sullivan, 1983).

La Jolla

Somewhere in Rose Canyon the sense of throw on the Rose Canyon fault reverses and near La Jolla shores the gravity data suggest a throw, up-to-the-southwest, of about two thousand feet (Fig. 12). The bench in the gravity profile suggests some of this displacement occurred on a fault about 2000 feet north of the main strand. Unlike the Country Club fault, Kennedy's Muirlands fault has a significant amount, i.e., about 500 feet, of throw (Kennedy and Peterson, 1975).

A TECTONIC MODEL

Kennedy et al. (1975, p.25) suggested that the fault pattern around San Diego Bay implied that the basin is a nested graben in an area of tension between two right-stepping strands of the Rose Canyon fault zone, i.e., is a rhombochasm. Rhombochasms occur where the strike-slip boundary between two moving plates bends in such a way as to create a zone of tension and, if the crust were rigid, a chasm with a rhomohedral shape (Crowell, 1984, 1987). Rhombochasms on a larger scale and more advanced stage of crustal extension are found to the east in the Salton Trough and are associated with right steps in the San Andreas fault zone (Crowell and Sylvester, 1979). Such basins in the continental crust are, in effect, small spreading centers. Not only are the deep basins in the Salton Trough the on-land equivalents of the spreading centers in the Gulf of California, they are their predecessors. The Gulf itself originated by the coalescence of such basins formed along NE-SW bends in the NW-SE trending Pacific-North American plate boundary. A crustal basin or depression such as the San Diego basin forms as the ductile middle to lower crust stretches and thins (Fig. 13). The upper, brittle crust slumps into the depression along faults that are often considered to shallow at depths, i.e., are listric normal faults. The gravity and fault data suggest the zone of crustal extension and thinning, i.e., the rhombochasm, trends about 10 degrees west of north, is centered near the south end of San Diego Bay, and extends from about downtown San Diego to several miles south of the U.S.-Mexico border. It is bounded by the 14 mile wide zone of normal-slip faults extending from the Pt. Loma fault zone on the west to the La Nacion fault zone on the east (Fig. 14). The more NW-trending, strike-slip Rose Canyon fault clearly forms its northern extension. The strike-slip fault at its southern end is less obvious, although a previously unknown, possibly strike-slip fault, in this area is reported by Artim et al. in this volume. Such a fault is aligned very closely with the Vallecitos--San Miguel fault zone.

The gravity and topographic high at Mt. Soledad probably result from the crustal compression that occurs when the Rose Canyon fault curves and trends more westerly than the general northwesterly Pacific-American plate relative motion. The fault must have a component of thrust slip here. A thrust plane dipping southerly under Mt. Soledad may explain why the folding and uplift of the sedimentary rocks is so much more intense south of the fault than to the north.

The effect that bends or divergences in the trend of strike-slip faults from the direction of the underlying relative plate motion may also explain the small basin beneath Mission Bay and the down-to-the-west throw of the Rose Canyon fault in this area. Since the fault trends N20W to N30W between Mission Valley and Rose Canyon, this interval should be a zone of tension. The fault here could have a slight dip-slip component, analogous to the La Nacion fault. In the Old Town area, where the fault trends more northwesterly, the down-to-the-west throw probably results from the right lateral, strike-slip juxtaposition of a more southern, deeper part of the basin on the SW against a more northern, shallower part on the NE.

Structural and Seismic Consequences of the Rhombochasm Model

Although the actual fault geometry and kinetics may be much more complicated than the simple rhombochasm model discussed above, to the extent that it is realistic, it has several important consequences. The first consequence of the Rose Canyon and the Pt. Loma--La Nacion fault zones being genetically connected and parts of the same fault system as shown in Fig. 14 is the explanation why the Rose Canyon fault has been so difficult to trace south of Mission Hills. It ceases to exist as a narrow, predominantly strike-slip fault zone and is transformed into the broad, predominantly dip-slip faults of the San Diego graben.

The second consequence is that the Rose Canyon and Pt. Loma--La Nacion fault zones are both either active or inactive. For one to continue to slip and the other not would be geometrically impossible. This doesn't mean both are identically seismogenic. Whether the narrow, strike-slip faults are capable of generating larger magnitude earthquakes than the broader zone of dip-slip faults of the San Diego graben is an important question. Can what is known of the seismic behavior of the more advanced basins in the Salton trough be applied to the San Diego basin? The clustering of local earthquakes during the past 50 years in south San Diego Bay, with only a few epicenters near the Rose Canyon fault, shows that the faults near the center of the graben have been the most active in the short term (Simons, 1977).

The third consequence of a rhombochasm model is that the slip rate on the Rose Canyon fault can be estimated if the amount of extension and age of sediments in the chasm are known. The strike-slip, SS, required to produce a given amount of extension, EX, is SS = EX/sin A, where A is the horizontal angle between the trend of the strike-slip fault and that of the graben. Assuming the overall trend of the Rose Canyon fault is N40W, like that of the Pacific-American plate relative motion in southern California, and a trend of the San Diego graben of N10W, A is about 30 degrees (Engebretson, et al., 1985; Fig. 3, this paper). There are several ways of estimating the extension across the San Diego graben, given the depth of the basin. One is based on the horizontal extension, or heave, that accompanies the vertical displacement, or throw, on normal faults in the brittle upper crust. The other uses the relation between the horizontal extension and vertical thinning of the ductile zone beneath the faulted crust.

The relation between extension, EX, and throw, T, on a single normal fault is EX = T/tan d, where d is the fault dip (Fig. 15a). In a graben bounded by two sets of normal faults, EX = 2D/tan d, where D is the depth of the graben (Fig. 15b). Thus the amount of strike-slip, needed to produce a basin with a depth D is:

$$SS = 2D/(\tan d \sin A).$$

Elliott (1970) found that the deepest part of the basin contains about 6000 feet of sediments, of which about half are considered Plio-Pleistocene. The most uncertain and most important variable in the equation is the fault dip. Even though the dips measured by Kennedy et al. (1975) on the La Nacion fault strands are about 75 degrees, the fault planes may well shallow at depth as in Figure 13. The exact geometry of normal faults at depth in regions of continental extension is not well understood and is probably fairly complicated. In a world-wide review of fault-plane solutions for large (M>5.5), normal-slip, continental earthquakes, almost all nucleated at 6 to 15 km depth on fault planes dipping between 30 and 60 degrees (Jackson, 1987). For this reason, and simply because it is also midway between 0 and 90 degrees, an average dip of 45 degrees will be used in these calculations. Using a thickness of Plio-Pleistocene sediments of 3000 feet, or 1 km, and an A value of 30 degrees, yields a value of 4 km of post-Miocene strike-slip on the Rose Canyon fault. The importance of the dip value in this equation is seen by using the two extreme values. A dip of 90 degrees would yield no extension and no strike-slip, whereas as the dip approaches 0 degrees the extension and strike-slip rapidly approach infinity.

Using the relation between ductile stretching and thinning to calculate the required extension avoids any assumption of fault dip. The depth and the width of the graben equals that space created by the ductile extension and thinning of the crust beneath the basin. A vertical area of the crust with an original width, W_0, and thickness, Th_0, stretches to a larger width, W_1 and a reduced thickness, Th_1 (Fig. 15c). The cross-sectional area of the basin is its depth, D, times W_1. Assuming the density of the ductile layer is unchanged during extension, $W_0Th_0 = W_1Th_1$, and $Th_1 = Th_0\text{-}D$. Therefore, $W0Th_0=W_1Th_0\text{-}W_1D$, and the extension, EX, which is $W_1\text{-}W_0$, = W_1D/Th_0. The strike-slip, SS, needed to create a basin of depth D calculated by this method is:

$$SS = W_1D/(Th_0 \sin A)$$

The present width, W_1 of the graben is about 20km. In areas of large crustal extension, such as the Basin and Range Province, the zone of ductile stretching and thinning is considered to lie in the middle to lower crust, i.e., to be about 20 km thick (Gans,1987). Using the 1 km thickness, D, of Plio-Pleistocene sediments, the calculated crustal extension is 1 km, and the post-Miocene strike-slip on the Rose Canyon fault is 2 km. This is close to the value of 4 km found in the preceding method using an average dip of 45 degrees. Using simple models and mathematical formulas based on them can be misleading because nature is usually more complicated than our often naive concepts. However, they have the advantage that the consequences of a model are testable and each variable in the equations can be examined and semi-quantitative, geologically reasonable ranges can be assigned to each. As was seen above, the extension and strike-slip based on normal faulting is most sensitive to the assumed dip. In the crustal thinning method the thickness of the zone of extension and the shape of its lower surface are the key variables. The extension and strike-slip are inversely proportional to the assumed thickness of the ductily stretched layer. Doubling its thickness to 40 km reduces the calculated slip from 2 km to 1 km. Conversely, if the stretched layer actually necks and the basin above the thinned zone is mirrored by an upward bulge of the mantle beneath it, the extension and strike-slip required to create the sedimentary basin increases. A relief on the mantle bulge equal to the depth of the basin would double the calculated extension and slip rate.

In summary, if the Rose Canyon and Pt. Loma--La Nacion fault zones are geometrically related as parts of a rhombochasm, the well data indicating about 3000 feet, or 1 kilometer, of Plio-Pleistocene sediments under San Diego Bay suggest about 2 to 4 km of post-Miocene strike-slip on the Rose Canyon fault. Assuming an age of 6 MY at a depth of 1 km yields a post-Miocene slip rate of approximately 0.5 mm/Y -- somewhat slower than the Kennedy et al. (1975) value of 1 to 2 mm/Y since the Pliocene. The sediment depth also suggests that the post-Miocene, vertical component of the dip-slip on the Pt. Loma and La Nacion faults is 1 km. The dip-slip, DS, = D/sin d. For a D of 1 km and a dip of 45 degrees, DS is 1.4 km. This means that the post-Miocene, dip-slip rate on the fault zones bounding the graben is on the order of 0.2 mm/y. Since the strike-slip rate based on fault dip is inversely proportional to the tangent of the dip and the dip-slip rate is inversely proportional to the sine of the dip, and they use the same assumptions of depth and age of sediments, the ratio of the two estimates should be more exact than either one alone. The strike-slip to dip-slip ratio, SS/DS = 4 cos d, and is thus fairly insensitive to dip for dips ranging from zero to 60 degrees. Regardless of the exact listric nature of the graben faults, the strike-slip rate on the Rose Canyon fault should be about 4/1.4, or about three times the dip-slip rate on the graben faults.

SUMMARY AND CONCLUSIONS

Of the various geophysical techniques, the twelve detailed gravity profiles presented here probably are second only to reflection seismic profiles in resembling geologic cross-sections. They support the observation of previous workers that the San Diego Basin is a nested graben and help define which strands of the bounding faults are responsible for most of the vertical slip. At the south end of San Diego Bay, where the basement is about 3000 to 5000 feet deep, the smooth slope of the gravity profile has only a few, short wavelength anomalies where faulting has caused near-surface density contrasts, but the position of its center shows that the center of faulting lies midway between I-5 and I-805 -- about two miles to the west of most of the mapped traces of the La Nacion fault.

Further to the north, downtown San Diego lies on the axis of the graben which has shallowed to about 4000 feet and is bounded on the east by several strands of the La Nacion fault between Euclid and 60th St. that have two to three thousand feet of throw. West of downtown San Diego geologic mapping shows the graben to be bounded by the northward extension of off-shore faults such as the Spanish Bight and Coronado fault zones and various strands of the Pt. Loma fault zone along Nimitz Blvd. and on Pt. Loma Peninsula (Kennedy and Welday, 1980; Kennedy et al., 1975). The gravity data along Harbor Drive, however, strongly suggest that the vertical displacement on these strands is small and that the major fault zone that has uplifted central Pt. Loma extends from Loma Portal through the Naval Training Center and into the harbor west of the Spanish Bight fault zone.

Gravity profiles along three E-W streets in downtown San Diego fail to show the continuation of the Rose Canyon and Florida Canyon faults into this area. A notable exception is a well-defined anomaly on the northernmost traverse on Broadway near 12th, exactly where Kern (1989) has projected the Rose Canyon fault. The gravity data suggest a down-to-the-east fault almost paralleling Kettener Blvd. and a zone of discontinuous faulting extending east from about 12th street.

Two miles to the north of downtown San Diego, the San Diego graben is asymmetric and has much less relief. The narrow Loma Portal zone of the Pt. Loma fault zone continues to have several thousand feet of throw but the eastern part of the graben is bounded by faults, such as the 30th--Texas St. and La Nacion faults that are spaced several miles apart and have only 500 to 1000 feet of throw. The Rose Canyon fault has 500 to 1000 feet of down-to-the-west throw. The northward strike-slip translation of a deeper part of the basin on the west probably causes this sense of throw and, at the same time, the asymmetry in the crustal profile. A shallow graben centered near Hwy. 163 between Mission Hills and Texas Streets appears to be the northward extension of the San Diego graben.

The Pt. Loma fault zone is not seen as a distinct step in the gravity profiles north of the San Diego River. The general structure under Mission Bay seems to be a basin sloping gently eastward to a basement high caused by 500 to 1000 feet of throw on the Rose Canyon fault.

The sense of throw on the Rose Canyon fault reverses in Rose Canyon and Mt. Soledad is caused by several thousand feet of throw, up on the southwest. This vertical displacement probably occurs on thrust faults--on the tilted plane of the Rose Canyon fault and/or separate thrust planes. Southwest dipping thrusts may explain why almost all the uplift and folding occurs southwest of the Rose Canyon fault. Of the faults mapped in La Jolla, only Kennedy's Muirlands fault has measurable throw.

Most of the crustal structure suggested by the gravity profiles in this study can be explained by divergences in the trend of the Rose Canyon fault from the northwesterly direction of relative motion in this zone between the Pacific and North American plates.

The compression that has folded and uplifted the strata of Mt. Soledad is due to a westward bend of the Rose Canyon fault to a trend of N60W. The small basin of Mission Bay may be due to the N20W-N30W trend of the fault between Old Town and Rose Canyon.

The most important structure along the fault is the nested graben, or rhombochasm, under San Diego Bay formed by a thirty degree northward bend in the Rose Canyon fault. The rhombochasm is about 12 miles wide, 16 miles long, and is centered near the south end of San Diego Bay. It trends about N10W and extends from downtown San Diego to several miles south of the U.S.-Mexico border. The geometric connection of the Rose Canyon fault to a nested graben explains why the Rose Canyon fault doesn't appear to continue south much beyond Mission Hills. Any strike-slip is transformed to predominantly (?) dip-slip on the faults forming the graben, i.e., the La Nacion--Pt. Loma fault zones. At the southern end of the rhombochasm the strike-slip possibly continues along a fault that connects directly with the San Miguel fault zone some 30 km to the southeast. Such a geometric connection dictates that dip-slip on the Pt. Loma--La Nacion fault zones must ultimately result in strike-slip on the Rose Canyon fault, and vice-versa. This raises a number of important questions about differences in seismicity, i.e., magnitude and frequency of earthquakes, between these two parts of the system. The clustering of small (M<4) earthquakes during the past 50 years shows the central part of the graben is active. Do the numerous earthquakes there and the almost complete absence of epicenters near the Rose Canyon fault imply that the critical stress needed for slip is much lower in the part of the system under tension than in the part under compression as at Mt. Soledad? How much slip accumulates in the graben before slip occurs on the Rose Canyon fault? How much of what is known about the seismicity of the more advanced rhombochasms in the more active San Andreas fault system is applicable to San Diego seismicity? A critical question for our local seismicity is how much of the strike-slip on the San Miguel fault zone is transferred to the Rose Canyon fault via the rhombochasm and how much of it continues on an offshore extension of the San Miguel as proposed by Artim et al. in this volume?

A final, interesting question is the exact direction of the slip on the La Nacion--Pt. Loma fault zone. The slip on faults bounding oceanic rifts, where the transform faults are typically perpendicular to the spreading centers, is pure dip-slip. In the San Diego Bay rhombochasm the angle, A, between the Rose Canyon transform fault and the basin-bounding faults is only about 30 degrees, which suggests a strike-slip component on the La Nacion--Pt. Loma fault zone. For normal faults with a dip, d, the strike-slip/dip-slip ratio, SS/DS, = cos d/tan A. Thus, for steep dips of about 70 degrees, as observed along the La Nacion fault at the surface, SS/DS = 0.3. The net-slip would be predominantly dip-slip and would rake 70 degrees. For intermediate dips of about 45 degrees, SS/DS =1.2, giving the net-slip a rake of about 40 degrees. For shallow dips of 0 to 30 degrees, SS/DS = 1.6, which would make the net-slip predominantly strike-slip and rake about 35 degrees. The effect that a bend in the fault plane, as in listric faults, would have on these calculations is unclear. If the San Diego Bay basin faults are comparable to the normal, continental crust faults studied by Jackson (1987), i.e., generate earthquakes with hypocenters between six and fifteen kilometers deep on planes dipping between 30 to 60 degrees, their net-slip directions could range between predominantly strike-slip and predominantly dip-slip. Well-constrained hypocenters and focal mechanisms for earthquakes in the San Diego Bay area should help define the subsurface fault dips and slip vectors.

A post-Miocene strike-slip rate on the Rose Canyon fault of about 0.5 mm/Y was calculated by two methods. Each relies on the correctness of the rhombochasm model, the age and depth of sediments in the graben, and geologic assumptions about either the geometry of the normal faulting beneath the basin during the brittle extension of the upper crust or the geometry of the zone of ductile extension beneath the faulting. Given the uncertainty of the assumptions, a 0.5 mm/Y strike-slip rate is surprisingly similar to the 1-2 mm/Y post-Pliocene strike-slip rate found by Kennedy et al. (1975). A post-Miocene dip-slip rate on the Pt. Loma--La Nacion fault zone of 0.2 mm/Y was calculated using many of the same assumptions. The strike-slip rate on the Rose Canyon fault is about three times the dip-slip rate on the Pt. Loma--La Nacion fault zones.

<u>Acknowledgements.</u> I want to thank and acknowledge my many SDSU senior thesis students, especially Dennis Sullivan, who spent many hundreds of hours taking and reducing the gravity data presented here. Without their interest and careful work this report would not have been possible. I also thank Leslie Herrmann and, especially, Diane Rice for their considerable help with typing, Teresa Larson for her beautiful drafting, and Gordon Gastil, Eric Frost, Pat Abbott, and John Meyer for their suggestions and inspiration.

FIGURE CAPTIONS

Figure 1. Location of detailed gravity profiles. PA-OT: Palm Ave. and Main St.-Otay Rd. at south end of San Diego Bay; HD-BR-MA-IM: Harbor Drive, Broadway, Market, and Imperial Ave. in downtown San Diego; BA-UN: Barnett-University Ave.; JE-MV: west end of middle jetty on San Diego River-Friars Rd.; SMB-TE: South Mission Beach-Tecolote Rd.; NMB-CD: North Mission Beach-Clairemont Dr.; NMB-BA: North Mission Beach-Balboa Ave.; LJ: Stations were made along a NE-SW line

extending south from La Jolla Shores up Torrey Pines Rd., along Virginia Way, north of La Jolla School and High School to the coast at Neptune Park. Location of on-shore faults from Kennedy et al. (1975), location of off-shore faults from Kennedy and Welday (1980).

Figure 2. Bouguer anomaly map of Elliott (1970) with the location of the detailed gravity surveys in this study. Contour interval is 5 mgal.

Figure 3. Elliott's (1970) contour map showing depth below sea level to the crystalline basement (granitic and metavolcanic rocks) and location of our gravity profiles. Depths to basement were estimated by him from the gravity data in Figure 2 combined with well data. Contour interval is one thousand feet.

Figure 4. Illustration of the form of the gravity anomaly over a fault which has juxtaposed high density basement rocks against lower density sediments or sedimentary rocks. The midpoint on the step in the curve, or the inflection point, defines the location of the fault. The amplitude of the step is a measure of the throw or vertical offset. The steepness, or gradient, of the step is a measure of the depth to the density contrast. increases the step becomes less sharp and changes to a gentle slope. The horizontal distance in this plot is in thousands of feet, T is 200 ft., and the density contrast is 0.6 gm/cc.

Figure 5. Bouguer anomaly profiles at south end of San Diego Bay (See Fig. 1 for location). Unlabeled arrows are mapped locations of strands of the La Nacion fault zone with downthrown side indicated. F?, gravity suggested fault locations.

Figure 6. Composite Bouguer anomaly profiles along Harbor Drive, through downtown San Diego, and east along Imperial Avenue (See Fig. 1 for locations). Unlabeled arrows at east end are mapped strands of the La Nacion fault zone with downthrown sides indicated. Unlabeled arrows on Harbor Drive are extrapolated locations of Kennedy and Welday's (1980) Spanish Bight fault strands. F?, as in Fig. 5.

Figure 7. Enlargement of the gravity anomalies in downtown San Diego. Arrows with a K or a P are the extrapolated location of the Rose Canyon fault as mapped by Kennedy et. al. (1975) and Kern (1989), respectively. Arrows with a FC are the extrapolated location of the Florida Canyon fault (Kern, 1989). D is 'downthrown' side where mapped. F is location of a possible fault based on the gravity curve.

Figure 8. Bougher anomaly profile extending from Barnett Ave. on the west to about 54th and University on the east (See Fig. 1). Arrow at east end is the mapped location of the La Nacion fault. Arrow east of I-5 is that of the Rose Canyon fault. F? as in Fig. 5.

Figure 9. Bougher anomaly profile from west end of the middle jetty to the mouth of MIssion Valley (See Fig. 1). Arrows at east end are the mapped traces of the Rose Canyon fault with their sense of throw (Kern, 1989). Arrow near west end is the trace of Kennedy's Pt. Loma fault (Kennedy et al., 1975).

Figure 10. Bouguer anomaly profile across South Mission Bay east to Tecolote Canyon (See Fig. 1). Arrows at east end as in Fig. 9.

Figure 11. Bouguer anomaly profiles across North Mission Bay to the top of Clairemont Mesa (See Fig. 1). Arrows as in Fig. 9.

Figure 12. Gravity anomaly profile extending southwest from Scripps Institute of Oceanography (SIO) to Neptune Park in La Jolla (See Fig. 1). RC, CC, and M. traces of the Rose Canyon, Country Club, and Muirlands faults and their sense of throw as mapped by Kern (1989) and Kennedy et al. (1975).

Figure 13. Schematic block diagram of the nested graben of the San Diego Basin. The trough trends N-S, is centered under San Diego Bay, and extends from the U.S.-Mexico border to Mission Valley. It is bounded on the east by the La Nacion fault zone (which includes the Sweetwater fault). The faults that bound it on the west are largely underwater and extend for 6 miles west of Silver Strand and include the Silver Strand and Coronado (not shown here) and Spanish Bight fault zone (Kennedy and Welday, 1980). and the Pt. Loma fault zone as discussed in this paper.

Figure 14. A simple rhombochasm model for the generation of the San Diego basin. As the Pt. Loma-Mt. Soledad block moves northwest, a N-S zone of the middle and lower crust beneath San Diego Bay stretches and thins--creating a depression into which pieces of the upper crust slide, as in Fig. 13. This zone of crustal extension and large scale crustal 'slumping' is about 12 miles wide. The hachured zone merely shows the center of extension and the rhombohedral shape of the chasm that would be created if the crust behaved rigidly.

Figure 15. Schematic crustal cross-sections used in deriving crustal extensions by either normal faulting (a and b), or by ductile extension of a deeper layer (c). See test for definition of variables.

Gans, P.B., 1987, An open-system, two-layer crustal stretching model for the eastern Great Basin, Tectonics, v. 6, No. 1, p. 1-12.

Habel, Robert S., 1980, A gravity survey of the Sweetwater La Nacion fault zone in National City: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Hansen, Peter A., 1980, A gravity survey of east San Diego, San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Harrington, John, 1980, A gravity survey of Metropolitan San Diego, California: Unpublished Special Project, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Jackson, J.A., 1987, Active normal faulting and crustal extension, in Continental Extension Tectonics, Coward, M.P., J.F. Dewey, and P.L. Hancock (eds.), Geol. Soc. Spec. Pub. No. 28, p. 3-17.

Kennedy, M.P., and G.L. Peterson, 1975, Geology of the San Diego Metropolitan Area, California: California Division of Mines and Geology, Bulletin 200.

Kennedy, M.P., and E.E. Welday, 1980, Recency and character of faulting offshore Metropolitan San Diego, California: California Division of Mines and Geology Map Sheet 40.

Kennedy, M.P.; Tan, S.S.; Chapman, R.H.; and Chase, G.W., 1975, Character and recency of faulting, San Diego Metropolitan area, California: California Division of Mines and Geology. Special Report 123, 33p.

Kern, P., 1989, Unpublished fault maps of the La Jolla and Point Loma 7.5 minute quadrangles, Department of Geological Sciences, San Diego State University, San Diego, California.

Lothamer, Richard T., 1978, A gravity survey over a portion of the La Nacion fault in San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Marshall, M., 1979, Geophysical survey of the La Nacion fault zone, San Diego, California; Abbott P.L. and W. J. Elliott (eds.), Earthquakes and other perils, San Diego region, GSA field trip guidebook published by San Diego Association of Geologists, pp. 73-81.

Nelson, Charles E., 1980, A gravity survey west of the La Nacion fault in south San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Newsom, Tom, 1983, A gravity survey of the Rose Canyon fault zone: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

O'Grady, Victor, 1981, A gravity survey of the Point Loma fault zone: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Oliver, H., 1980, Interpretation of the gravity map of California and its continental margin: California Division of Mines and Geology, Bulletin 205.

Owens, Jim, 1983, Gravity survey across the Rose Canyon fault zone: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Simmons, R. S., 1977, Seismicity of San Diego, 1934-1974: Bull? Seismo, Soc. Amer., v.67, no. 3, pp.809-826.

Skillin, Robert, 1979, A gravity survey of the Rose Canyon fault zone near Mission Bay, San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Spencer, E., 1988, Introduction to the Structure of the Earth: McGraw Hill Publishers, New York.

Sullivan, Dennis, 1983, A Bouguer gravity map of the San Diego Metropolitan area, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

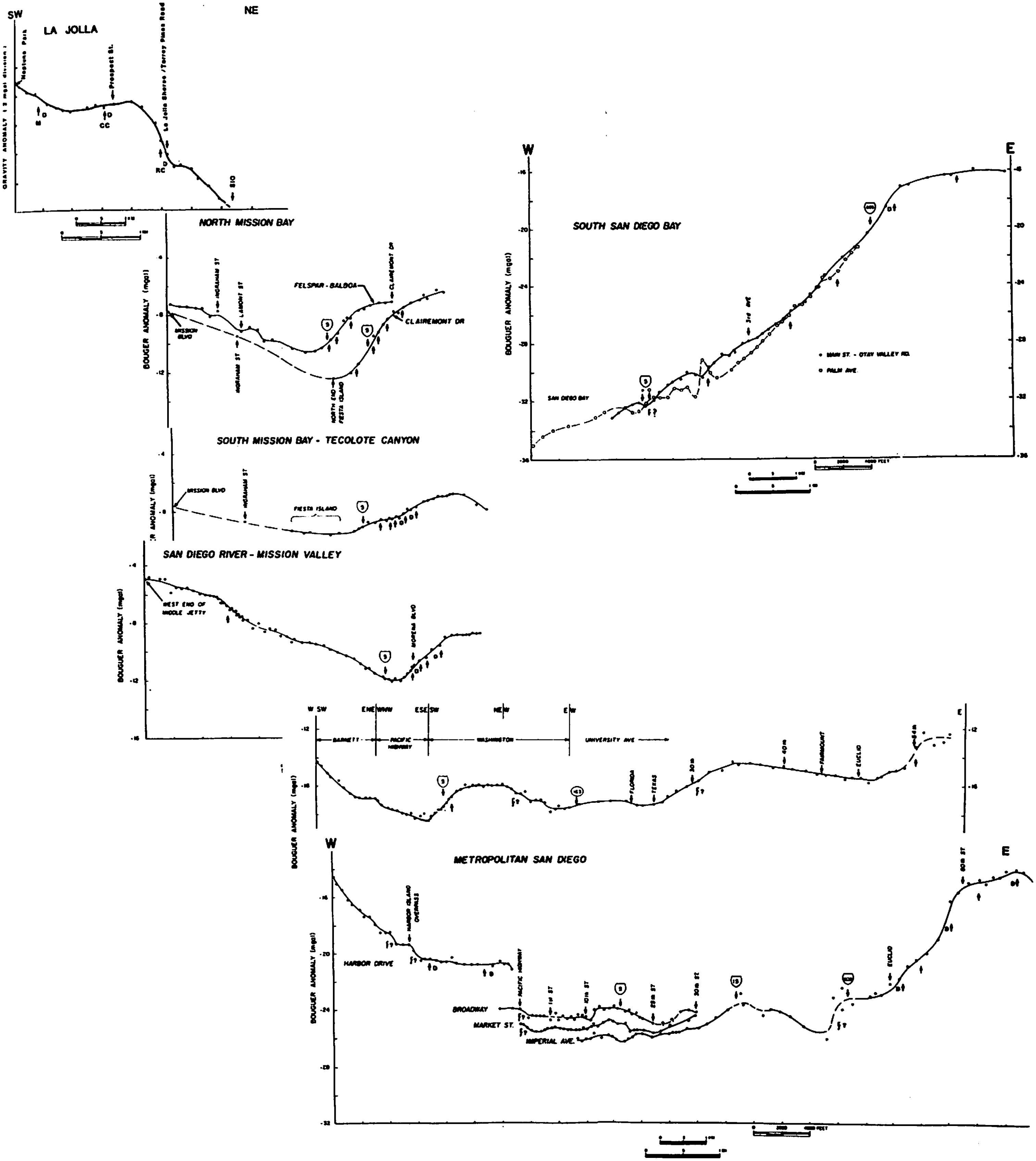
Tandy, Curt, 1979, A gravity survey of Coronado and North Island Naval Air Station, San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California .

Taylor, J., 1983, Friars Road gravity survey: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego, California.

Thom, Gerald E., 1979, Gravity survey of the Silver Strand, San Diego, California: Unpublished Senior Report, Dept. of Geological Sciences, San Diego State University, San Diego,California.

PLATE 1. DETAILED GRAVITY PROFILES

SAN DIEGO, CALIFORNIA



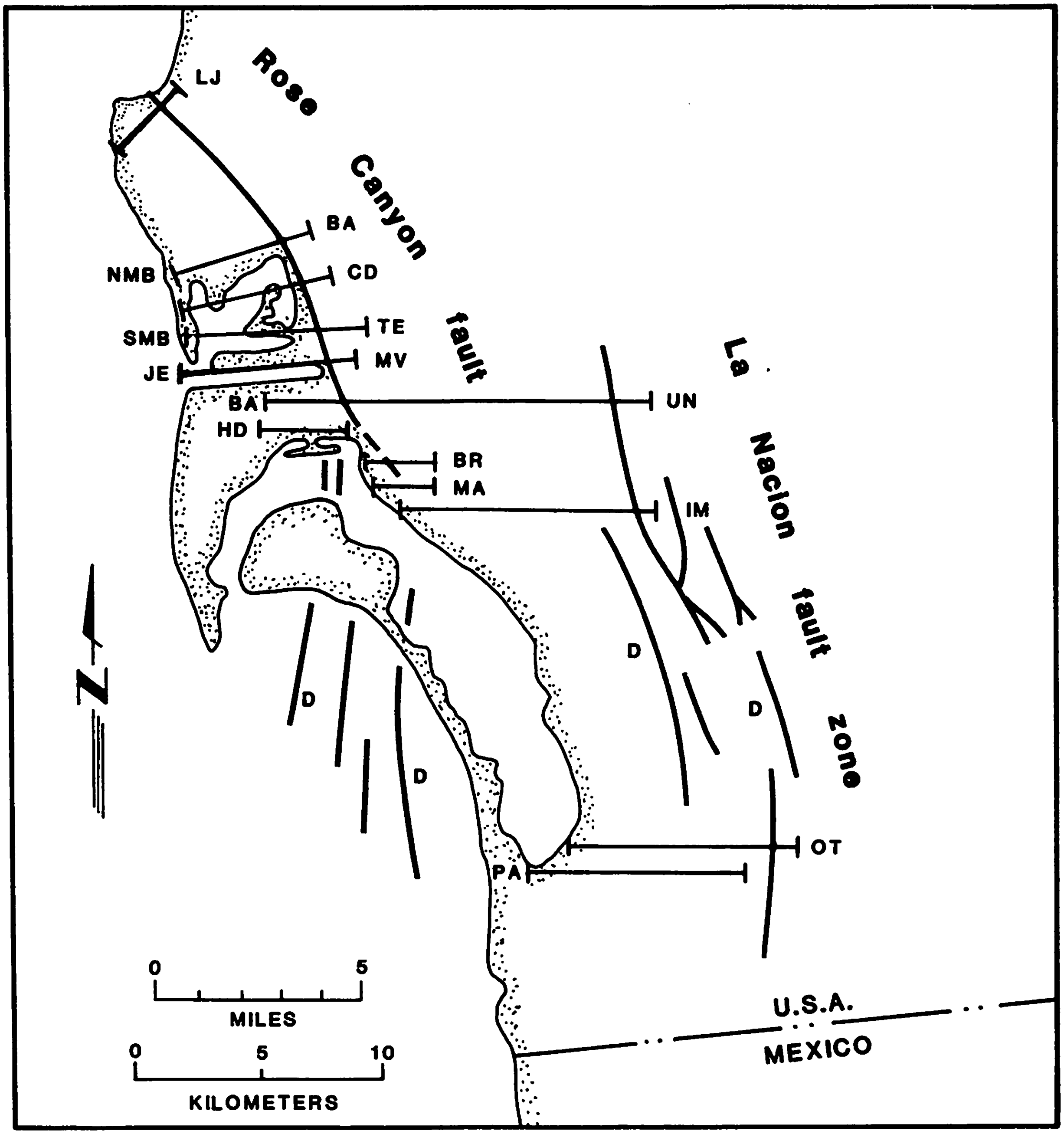


Fig. 1. Location of detailed gravity profiles. PA-OT: Palm Ave. and Main St.-Otay Rd. at south end of San Diego Bay; HD-BR-MA-IM: Harbor Drive, Broadway, Market, and Imperial Ave. in downtown San Diego; BA-UN: Barnett-University Ave.; JE-MV: west end of middle jetty on San Diego River-Friars Rd.; SMB-TE: South Mission Beach-Tecolote Rd.; NMB-CD: North Mission Beach-Clairemont Dr.; NMB-BA: North Mission Beach-Balboa Ave.; LJ: Stations were made along a NE-SW line extending south from La Jolla Shores up Torrey Pines Rd., along Virginia Way, north of La Jolla School and High School to the coast at Neptune Park. Location of on-shore faults from Kennedy et al. (1975), location of off-shore faults from Kennedy and Welday (1980).

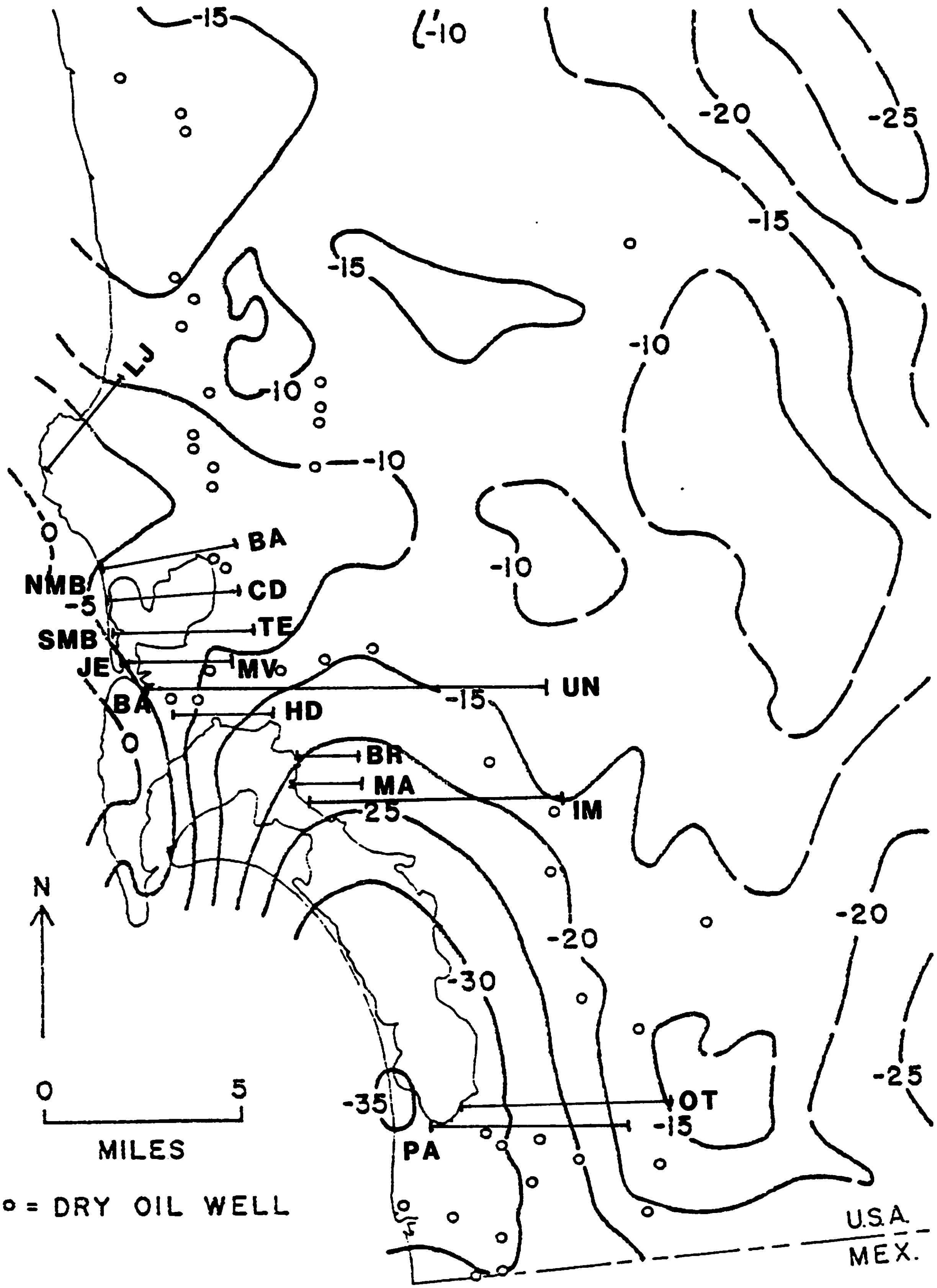


Fig. 2. Bouguer anomaly map of Elliott (1970) with the location of the detailed gravity surveys in this study. Contour interval is 5 mgal.

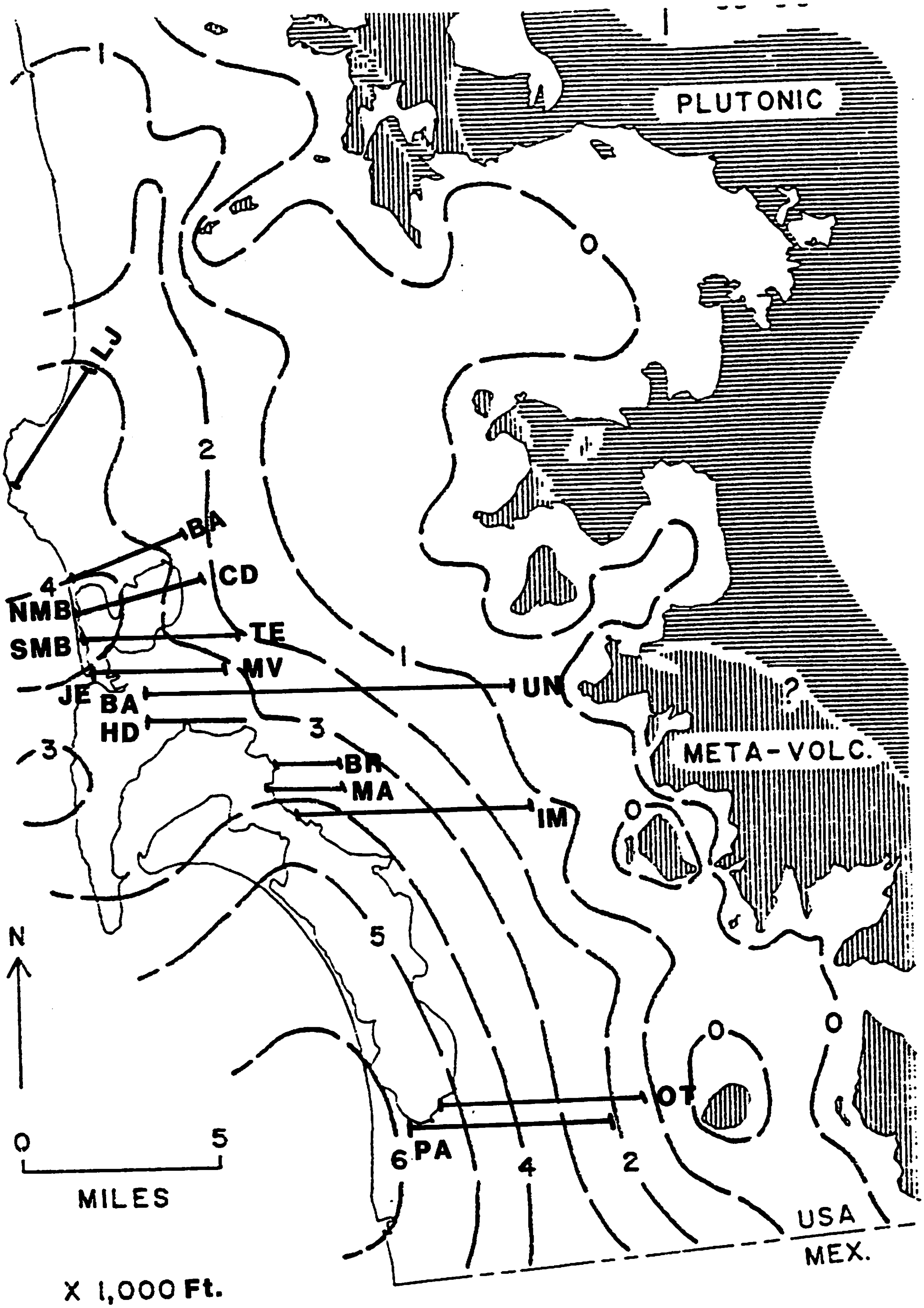


Fig. 3. Elliott's (1970) contour map showing depth below sea level to the crystalline basement (granitic and metavolcanic rocks) and location of our gravity profiles. Depths to basement were estimated by him from the gravity data in Figure 2 combined with well data. Contour interval is one thousand feet.

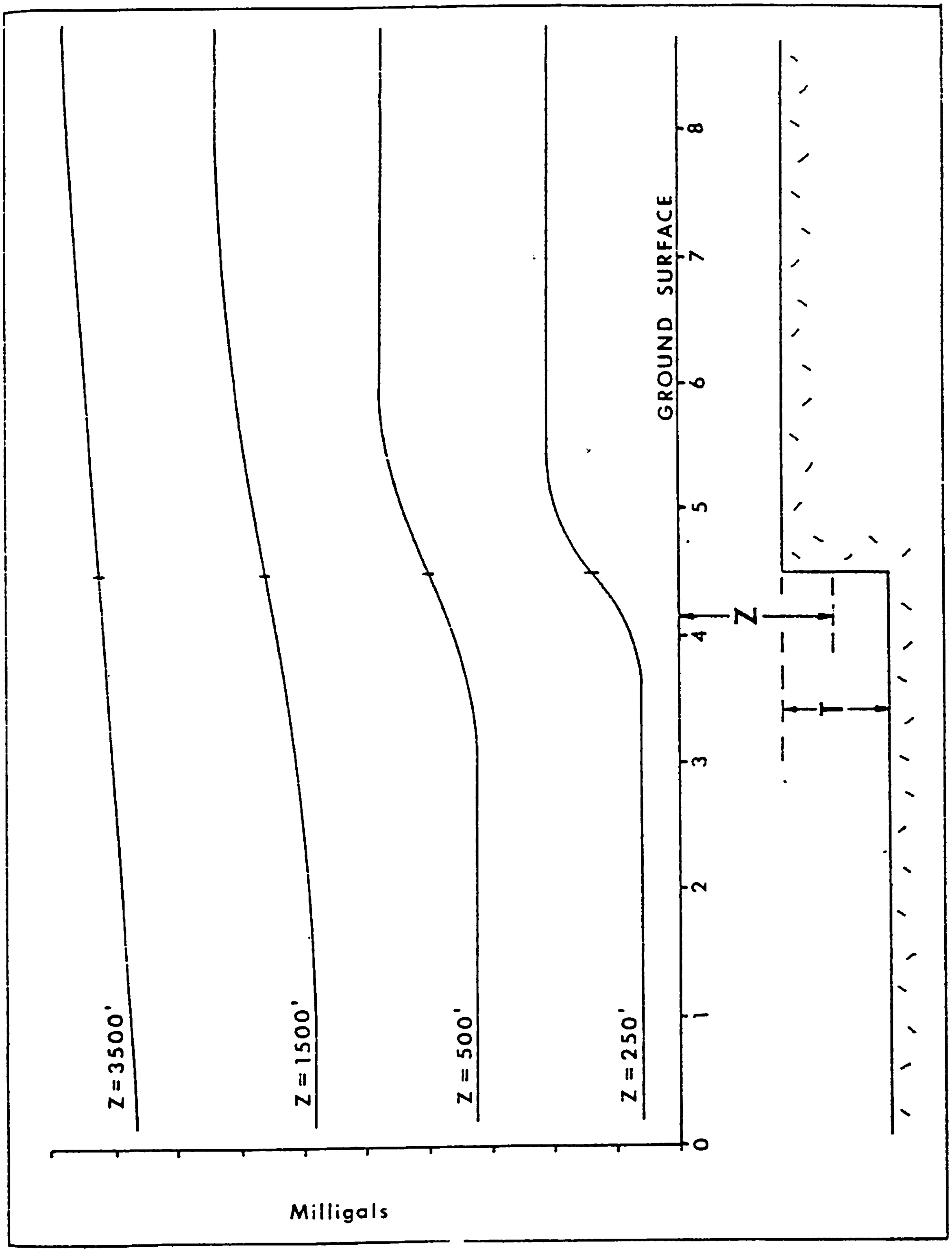


Fig. 4. Illustration of the form of the gravity anomaly over a fault which has juxtaposed high density basement rocks against lower density sediments or sedimentary rocks. The midpoint on the step in the curve, or the inflection point, defines the location of the fault. The amplitude of the step is a measure of the throw or vertical offset. The steepness, or gradient, of the step is a measure of the depth to the density contrast. increases the step becomes less sharp and changes to a gentle slope. The horizontal distance in this plot is in thousands of feet, T is 200 ft., and the density contrast is 0.6 gm/cc.

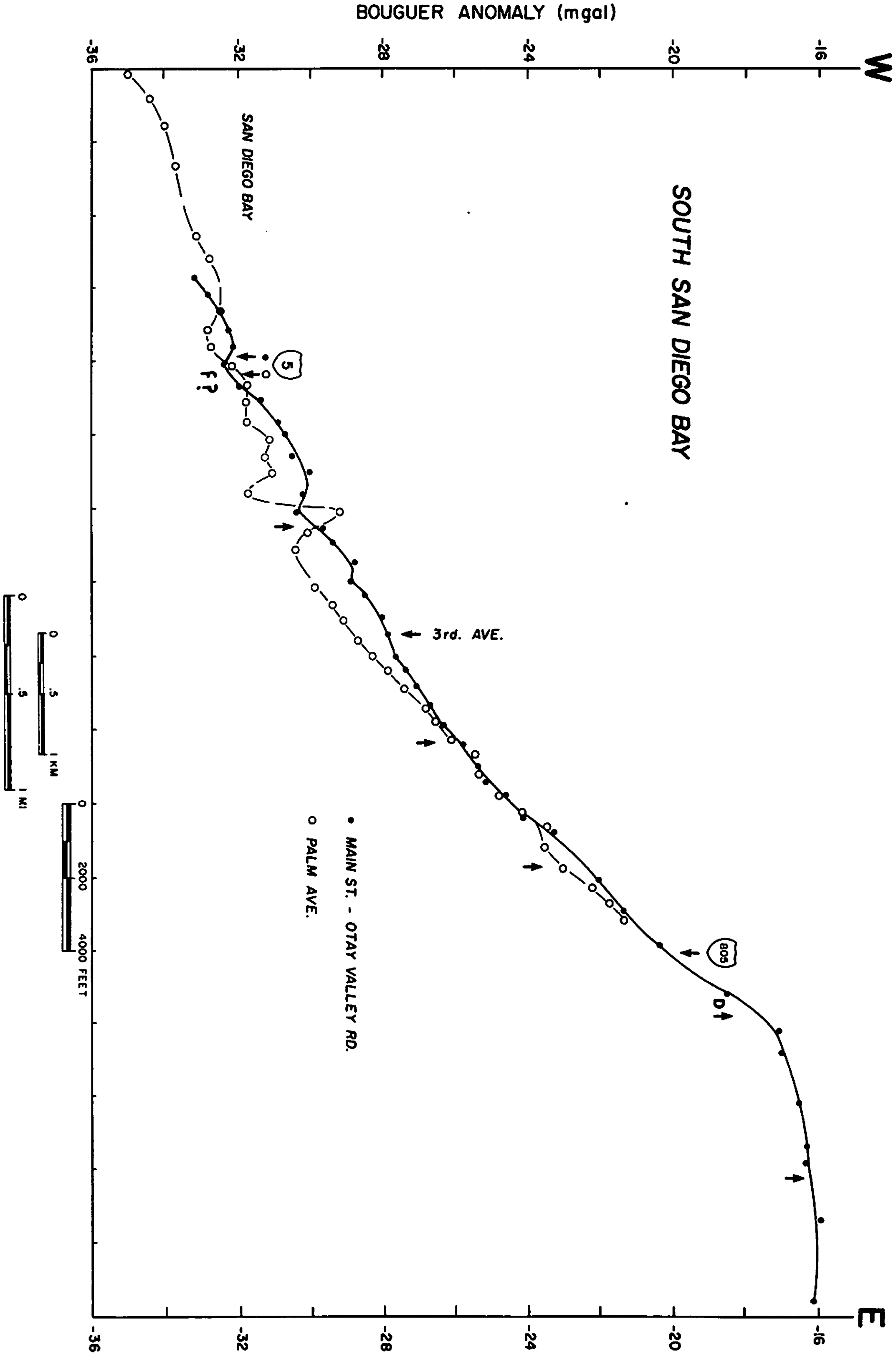


Fig. 5. Bouguer anomaly profiles at south end of San Diego Bay (See Fig. 1 for location). Unlabeled arrows are mapped locations of strands of the La Nacion fault zone with downthrown side indicated. F?, gravity suggested fault locations.

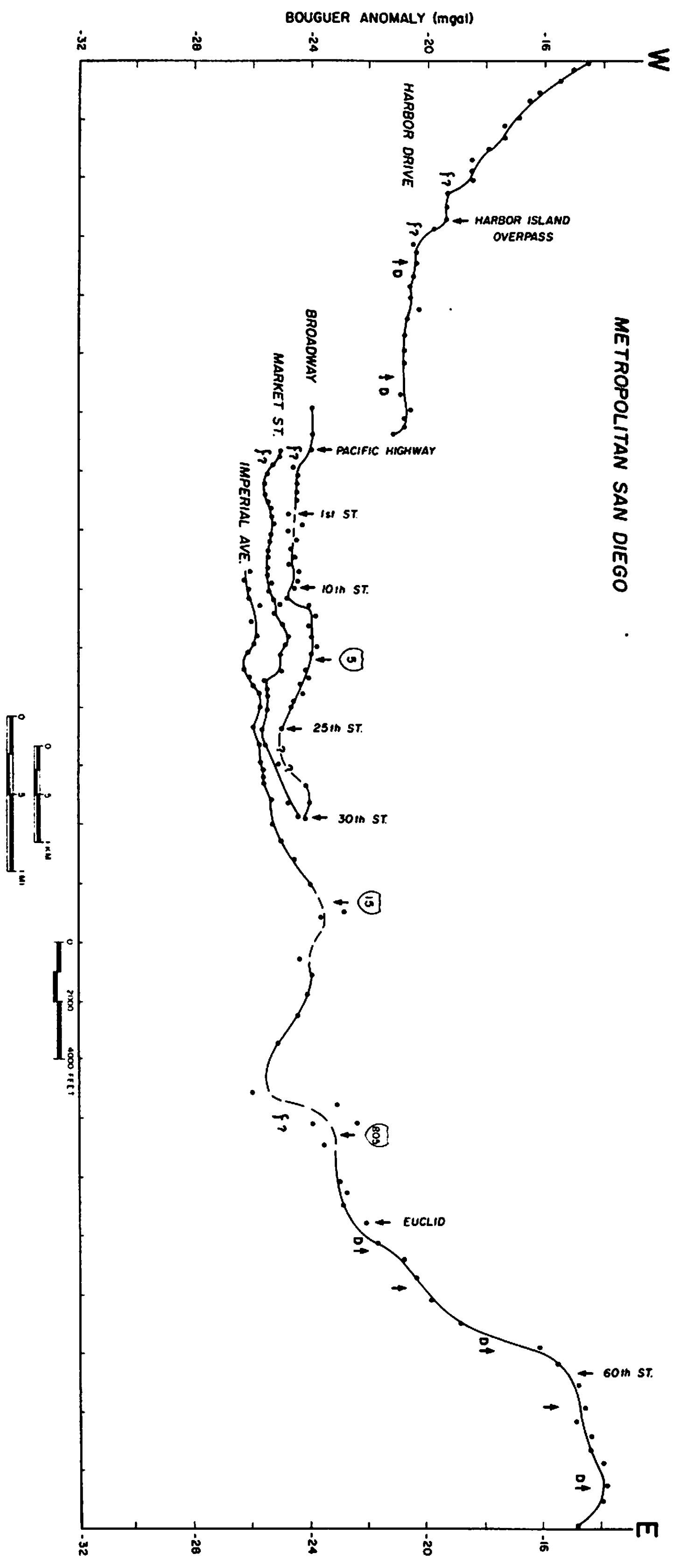


Fig. 6. Composite Bouguer anomaly profiles along Harbor Drive, through downtown San Diego, and east along Imperial Avenue (See Fig. 1 for locations). Unlabeled arrows at east end are mapped strands of the La Nacion fault zone with downthrown sides indicated. Unlabeled arrows on Harbor Drive are extrapolated locations of Kennedy and Welday's (1980) Spanish Bight fault strands. F?, as in Fig. 5.

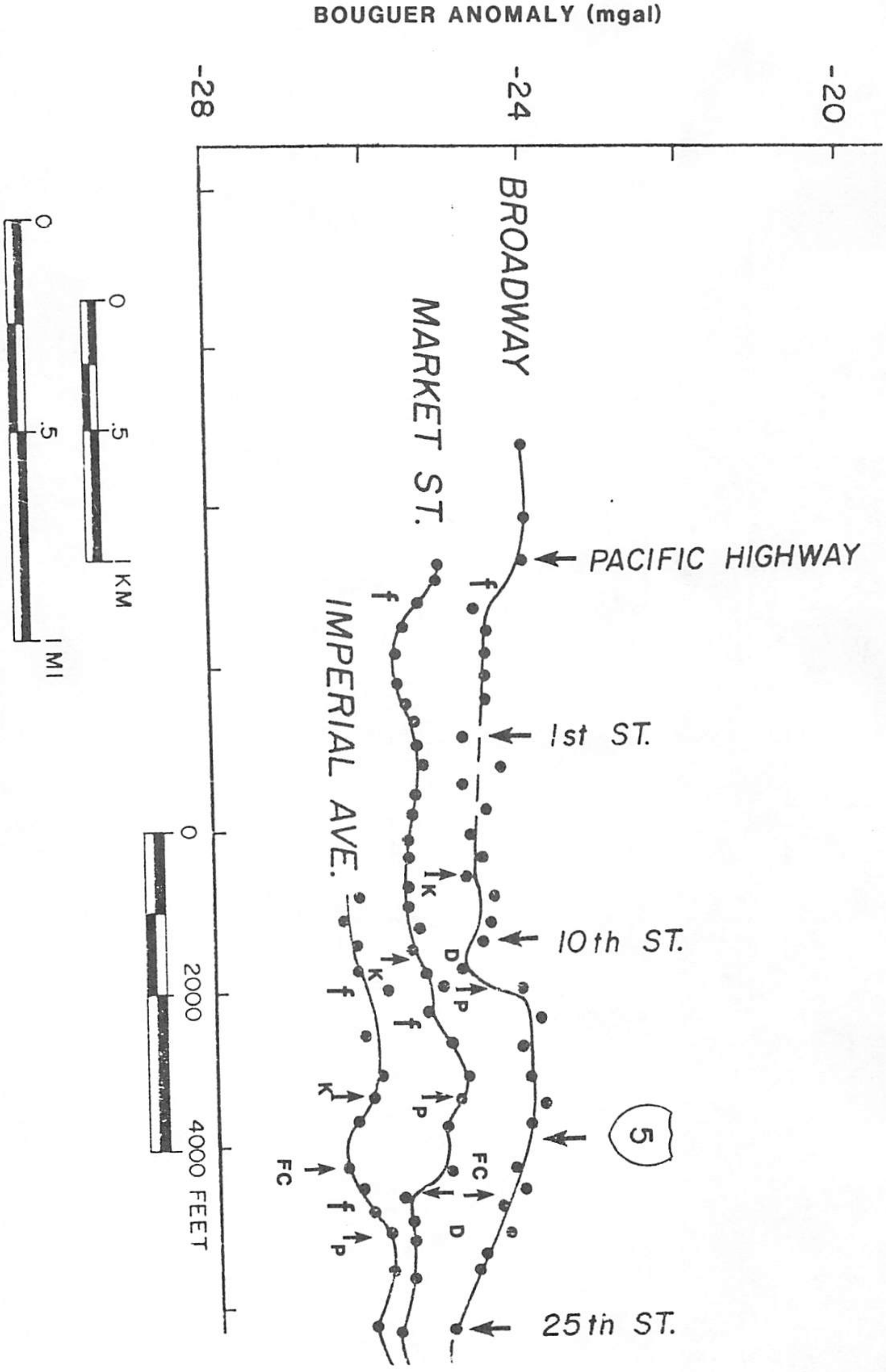


Fig. 7. Enlargement of the gravity anomalies in downtown San Diego. Arrows with a K or a P are the extrapolated location of the Rose Canyon fault as mapped by Kennedy et. al. (1975) and Kern (1989), respectively. Arrows with a FC are the extrapolated location of the Florida Canyon fault (Kern, 1989). D is 'downthrown' side where mapped. F is location of a possible fault based on the gravity curve.

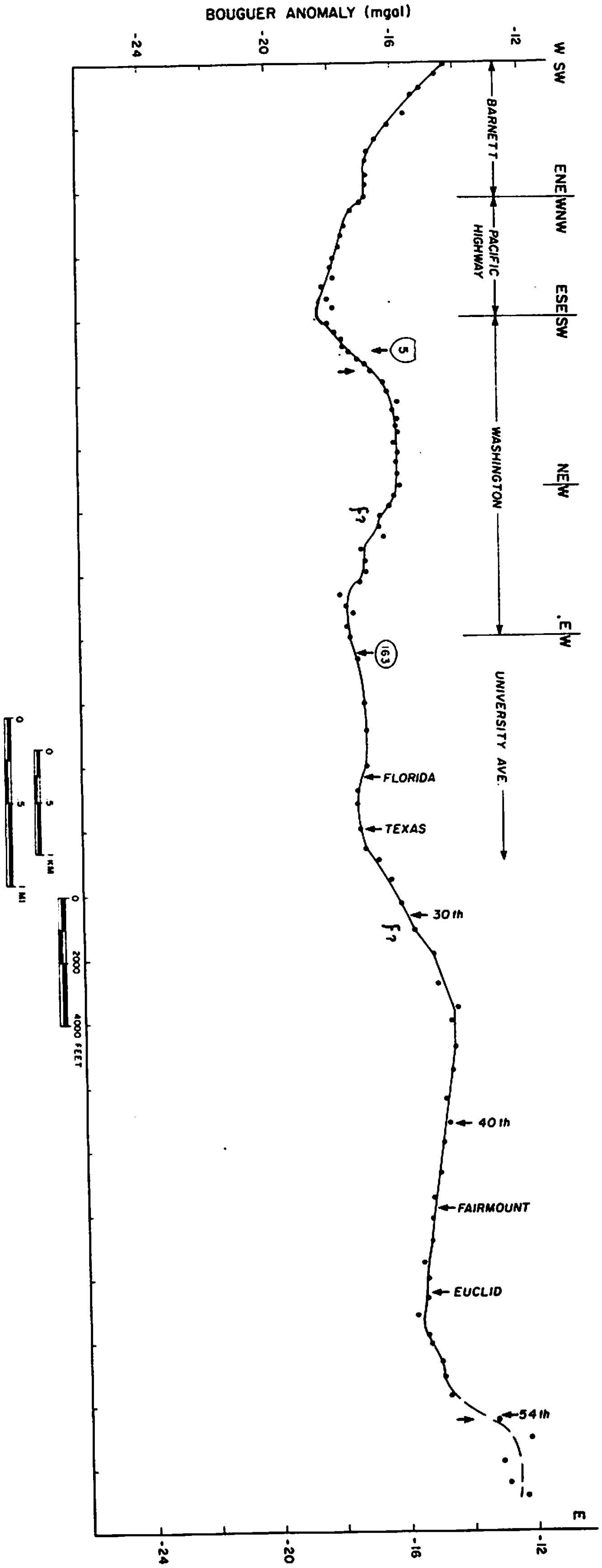


Fig. 8. Bougher anomaly profile extending from Barnett Ave. on the west to about 54th and University on the east (See Fig. 1). Arrow at east end is the mapped location of the La Nacion fault. Arrow east of I-5 is that of the Rose Canyon fault. F? as in Fig. 5.

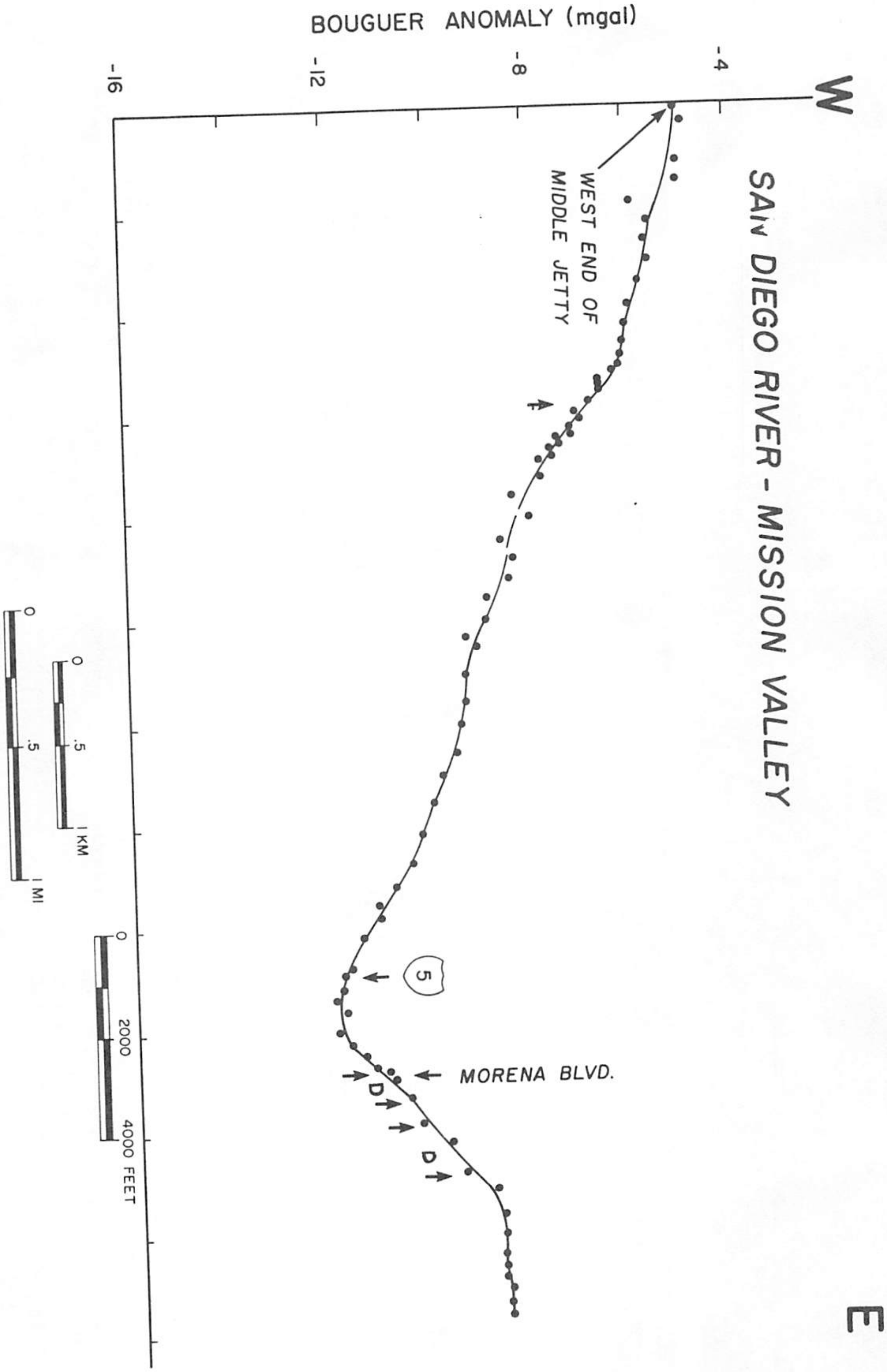


Fig. 9. Bougher anomaly profile from west end of the middle jetty to the mouth of MIssion Valley (See Fig. 1). Arrows at east end are the mapped traces of the Rose Canyon fault with their sense of throw (Kern, 1989). Arrow near west end is the trace of Kennedy's Pt. Loma fault (Kennedy et al., 1975).

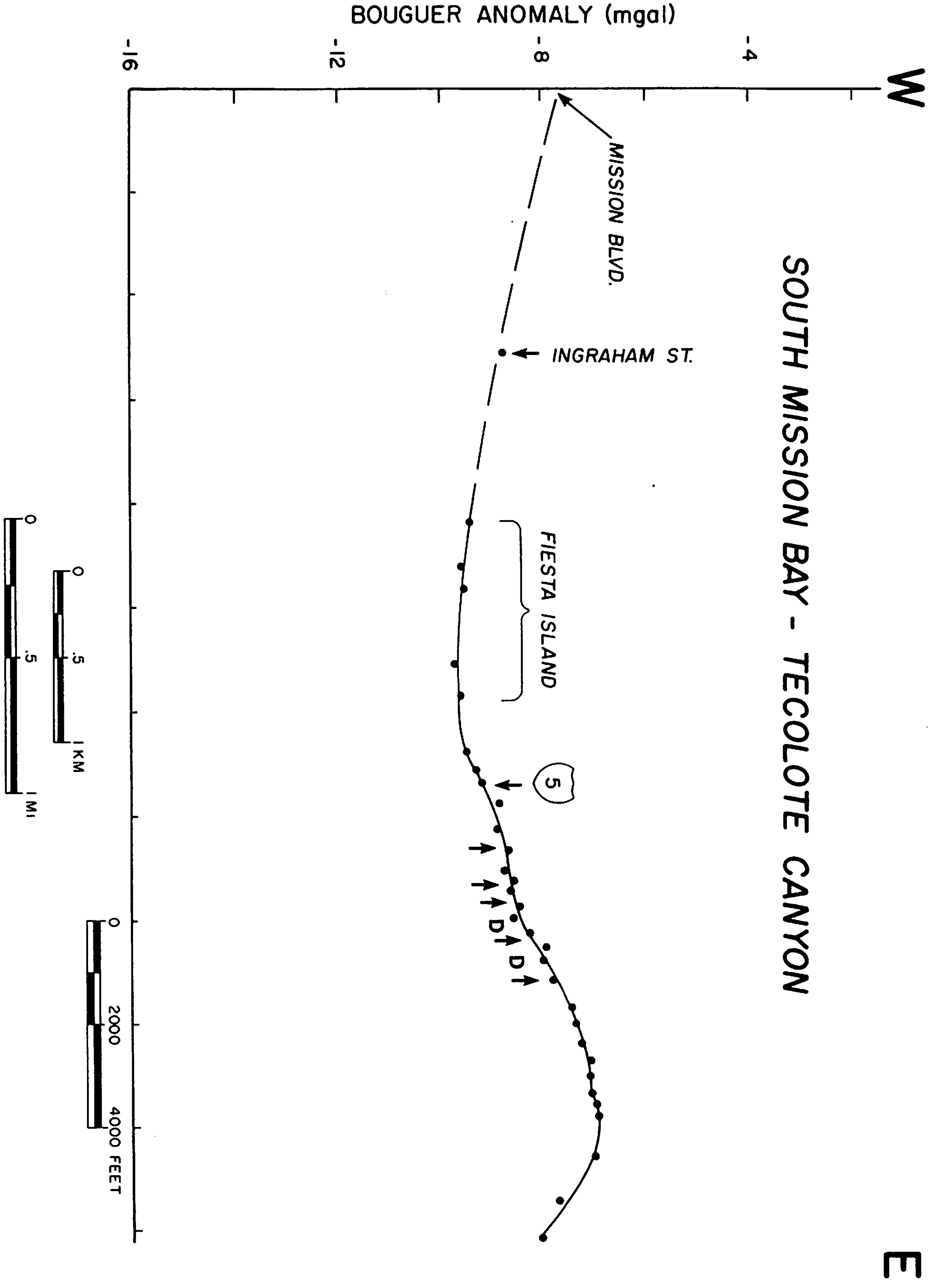


Fig. 10. Bouguer anomaly profile across South Mission Bay east to Tecolote Canyon (See Fig. 1). Arrows at east end as in Fig. 9.

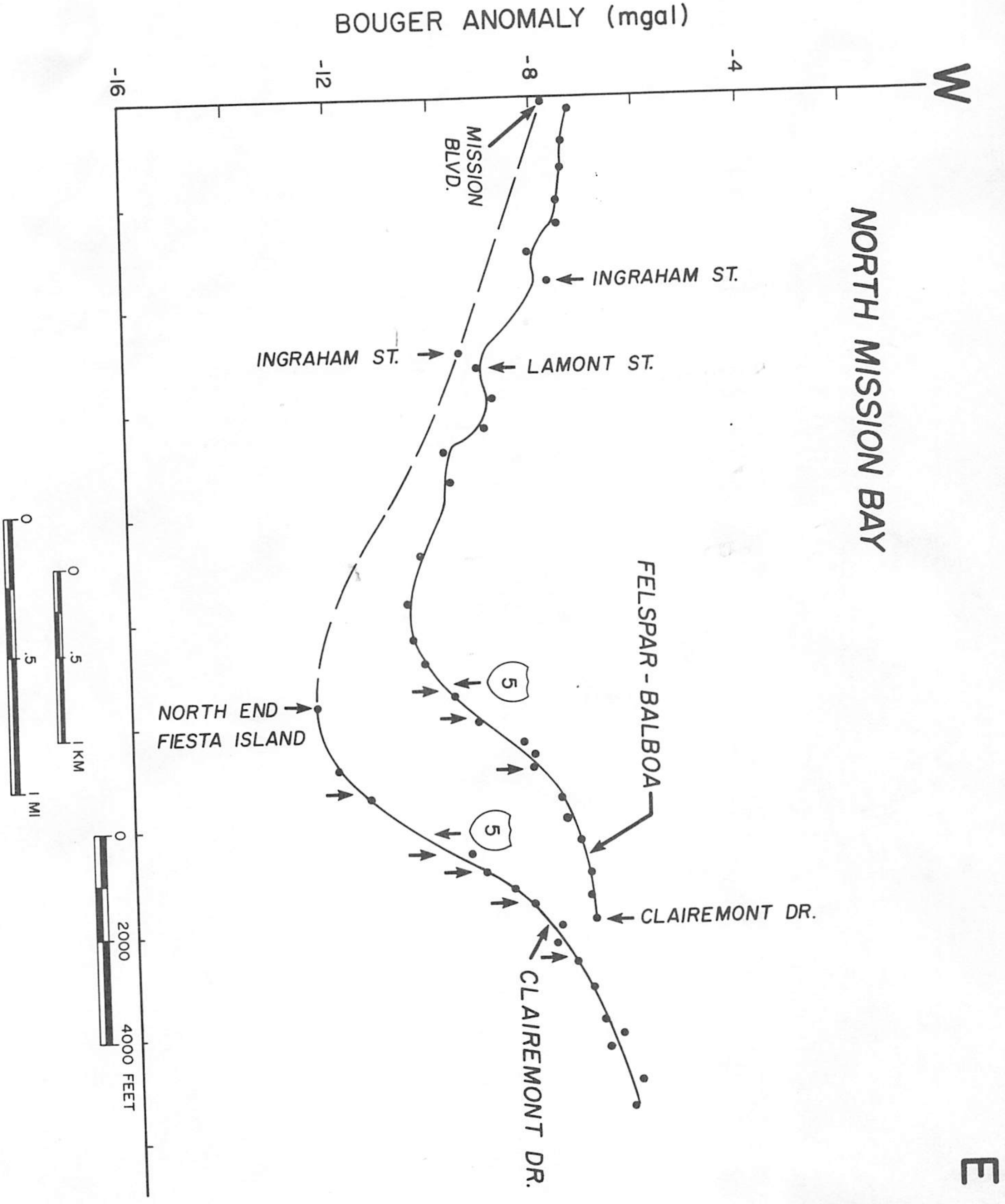


Fig. 11. Bouguer anomaly profiles across North Mission Bay to the top of Clairemont Mesa (See Fig. 1). Arrows as in Fig. 9.

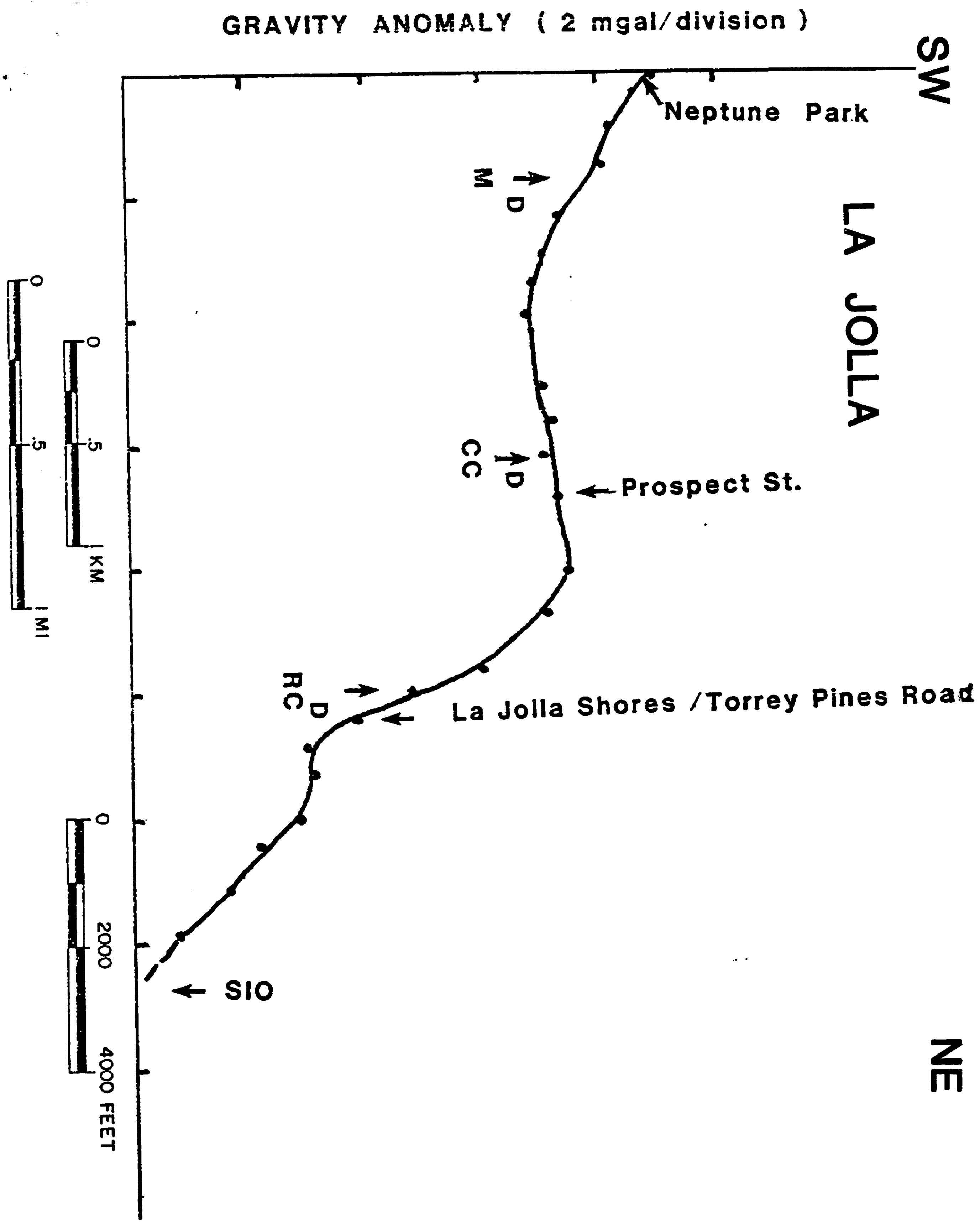


Fig. 12. Gravity anomaly profile extending southwest from Scripps Institute of Oceanography (SIO) to Neptune Park in La Jolla (See Fig. 1). RC, CC, and M. traces of the Rose Canyon, Country Club, and Muirlands faults and their sense of throw as mapped by Kern (1989) and Kennedy et al. (1975).

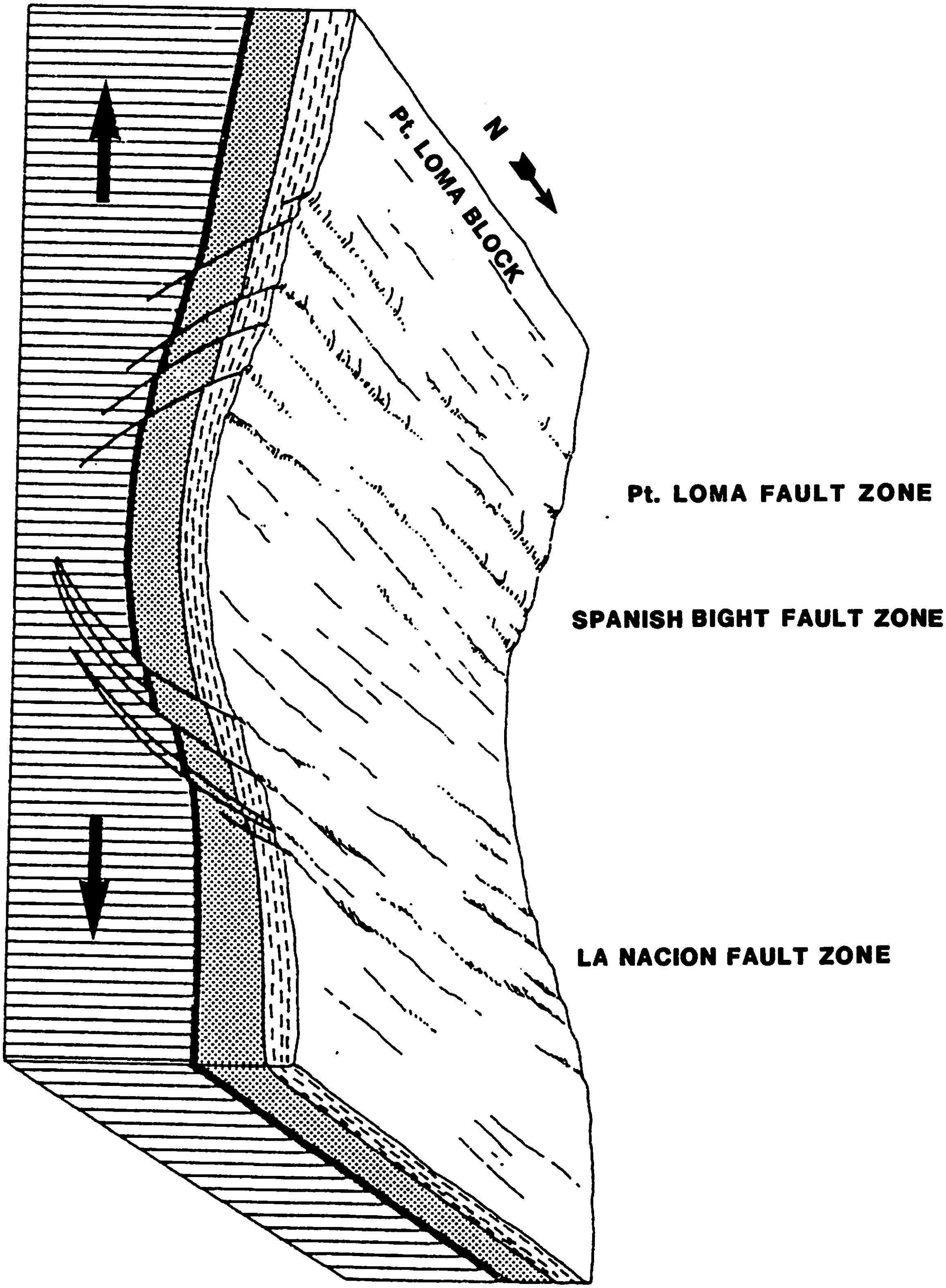


Fig. 13. Schematic block diagram of the nested graben of the San Diego Basin. The trough trends N-S, is centered under San Diego Bay, and extends from the U.S.-Mexico border to Mission Valley. It is bounded on the east by the La Nacion fault zone (which includes the Sweetwater fault). The faults that bound it on the west are largely underwater and extend for 6 miles west of Silver Strand and include the Silver Strand and Coronado (not shown here) and Spanish Bight fault zone (Kennedy and Welday, 1980). and the Pt. Loma fault zone as discussed in this paper.

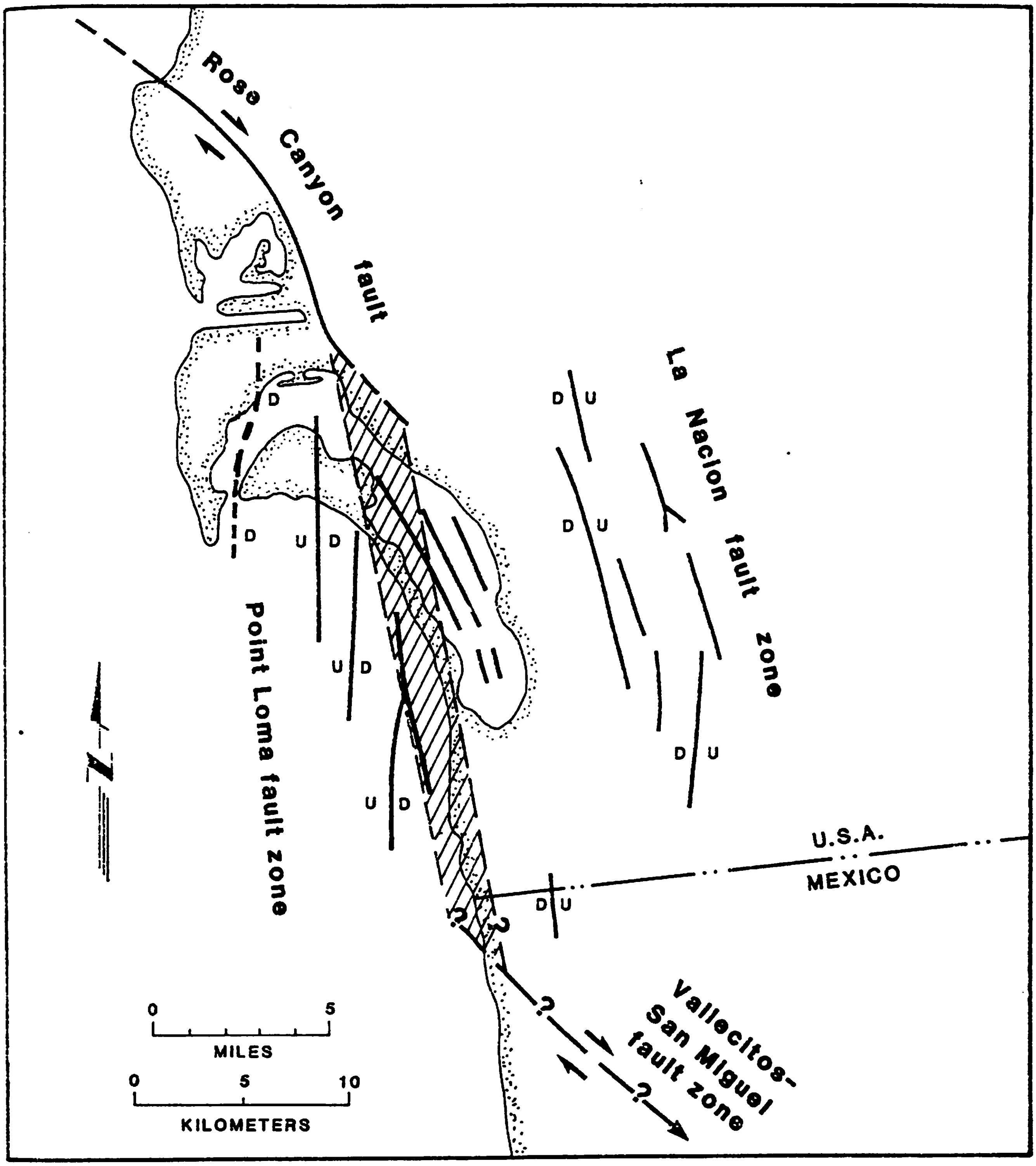


Fig. 14. A simple rhombochasm model for the generation of the San Diego basin. As the Pt. Loma-Mt. Soledad block moves northwest, a N-S zone of the middle and lower crust beneath San Diego Bay stretches and thins--creating a depression into which pieces of the upper crust slide, as in Fig. 13. This zone of crustal extension and large scale crustal 'slumping' is about 12 miles wide. The hachured zone merely shows the center of extension and the rhombohedral shape of the chasm that would be created if the crust behaved rigidly.

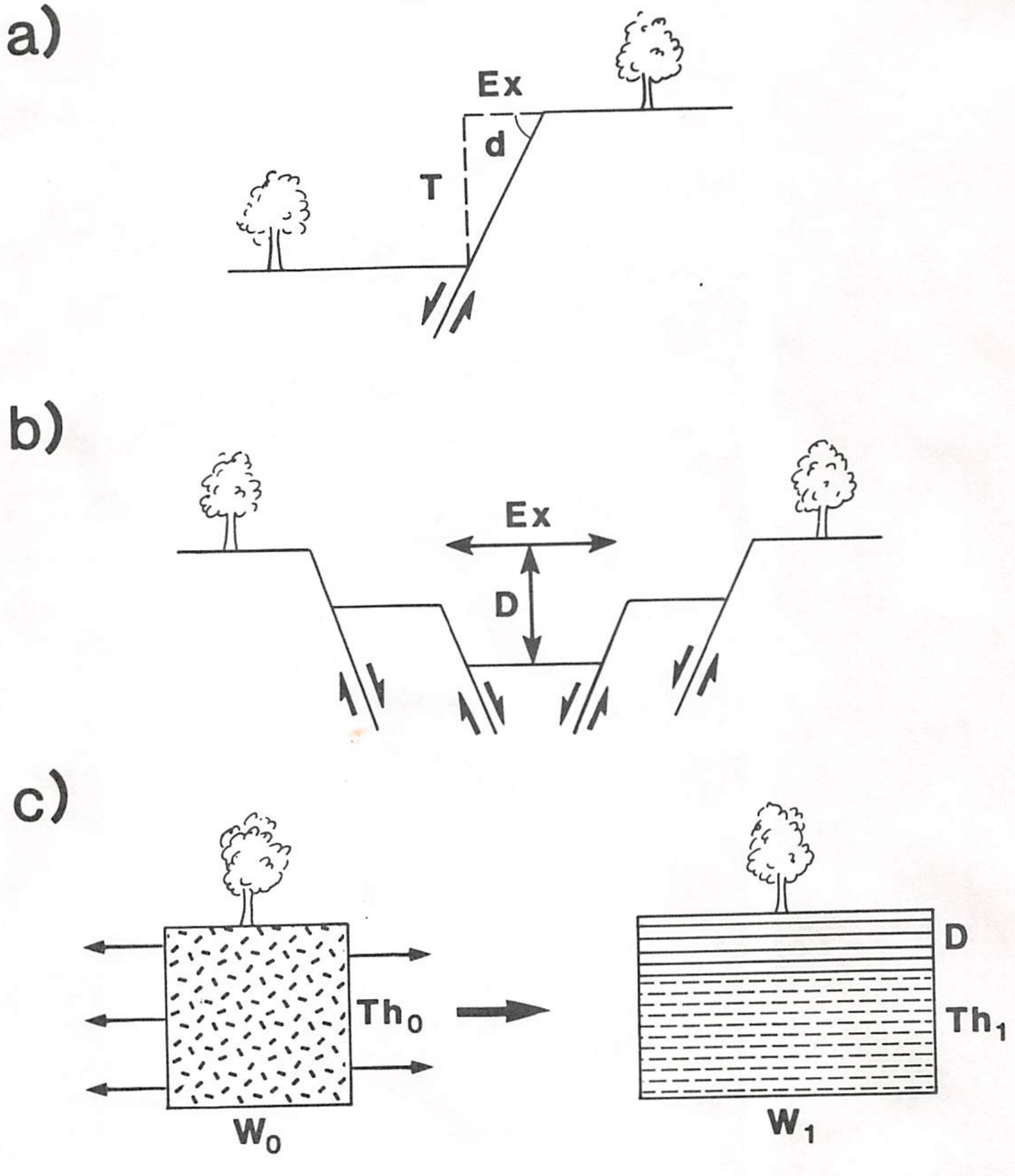


Fig. 15. Schematic crustal cross-sections used in deriving crustal extensions by either normal faulting (a and b), or by ductile extension of a deeper layer (c). See test for definition of variables.