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Title: CRUSTAL STRUCTURE OF THE CONTINENTAL BORDERLAND AND THE ADJACENT PORTION OF BAJA CALIFORNIA BETWEEN LATITUDES 30°N and 33°N

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Richard W. Couch

Gravity, magnetic and seismic data indicate that the oceanic crust is 9.7 km thick west of the Continental Borderland. The top of the mantle is about 12 km deep under the Borderland, and deepens to 27 km beneath the Peninsular Ranges of Baja California. The mantle is about 20 km below the surface of the Imperial Valley and deepens to 27 km under the area east of the Imperial Valley.

The age of the youngest detectable remnant magnetic anomaly over the oceanic crust is about 16.5 million years at 21.3°N Lat. and decreases to the south. A magnetic anomaly expected along the continuation of the San Benito Fault Zone is not detected by this study. A gravity low along the base of the Patton Escarpment is at least partially the result of a buried trench-like depression. In the vicinity of 31.3°N Lat., 119.3°W Long. this depression is filled with 2 km of sediments.

The geophysical and geological data are interpreted as indicating

a 6 km thick section of Franciscan rocks that extends from the west edge of the Borderland to the Coronado Escarpment. Magnetic data suggest that an ophiolite may be present within or on top of the Franciscan rocks.

Several of the ridges in the Borderland have cores of high density rocks which are interpreted as intrusives. The area just south of the San Clemente basin has an anomalously thin upper crust. The gross crustal structure of this region is comparable to the Imperial Valley region and may represent a former site of crustal rifting which occurred when the East Pacific Rise was subducted under this part of the North American plate. North of the Santo Tomas Fault Zone are several basins filled with more than 3 km of sediments, but south of this fault zone the sediment cover is discontinuous and generally less than 2 km thick.

# Crustal Structure of the Continental Borderland and the Adjacent Portion of Baja California between Latitudes 30°N and 33°N

by

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## INTRODUCTION

Most continental margins of the world have a basically simple morphology (Shepard, 1973). Starting at the coast there is usually a gently sloping, relatively smooth continental shelf. The continental shelf is typically about 75 km wide. The shelf break marks the beginning of the steeper (1 to 10 degrees) continental slope. At the base of the slope are the oceanic basins which average about 4 to 6 km deep. A trench may be present between the continental slope and the oceanic basin and can be as much as 10 km deep.

The west coast of North America between Bahia Vizcaino, Baja California, Mexico and Point Arguello, California, U.S.A. has a much more complicated physiography. Between the coast and the deep ocean basin is an elongate region, parallel to the coast, of highly irregular topography. Instead of the expected continental shelf and slope there is a complex continental margin consisting of basins and ridges, some of the latter protruding above the sea surface as islands. In places this anomalous pattern extends more than 200 km offshore. In order to emphasize the peculiar character of this region, Shepard and Emery (1941) named it the California Continental Borderland. In the following discussion it will often be referred to as the Continental Borderland or simply as the Borderland.

This thesis is concerned with the crustal and subcrustal structure of the Borderland and adjacent portions of California, Baja California, and the Gulf of California between latitudes $30^{\circ}$ and $33^{\circ}$N (Figure 1). To the west the area of study extends into the Pacific basin to approximately the 3.5 km bathymetric contour. To the east the study area extends to and includes the Gulf of California and the Imperial Valley trough. The area is studied by means of free-air gravity and magnetic data from the Borderland. This data is combined with available seismic, bathymetric, geological and Bouguer gravity data to construct two cross sections through the area of interest.

## Previous Work

Shor and Raitt (1958) published a crustal section from the Patton Escarpment at about $32.75^{\circ}$N Lat. through San Clemente Island. Based on seismic refraction data this section indicates that material with velocities typical of oceanic crust (6.7 km/sec) extends under the Borderland to the continent. However, material with velocities similar to continental crust (5 to 6 km/sec) is also present under many of the ridges and basins. Also the depth to the Moho increases systematically towards the continent. They suggested that the Borderland may be a transition zone between continental and oceanic crust.

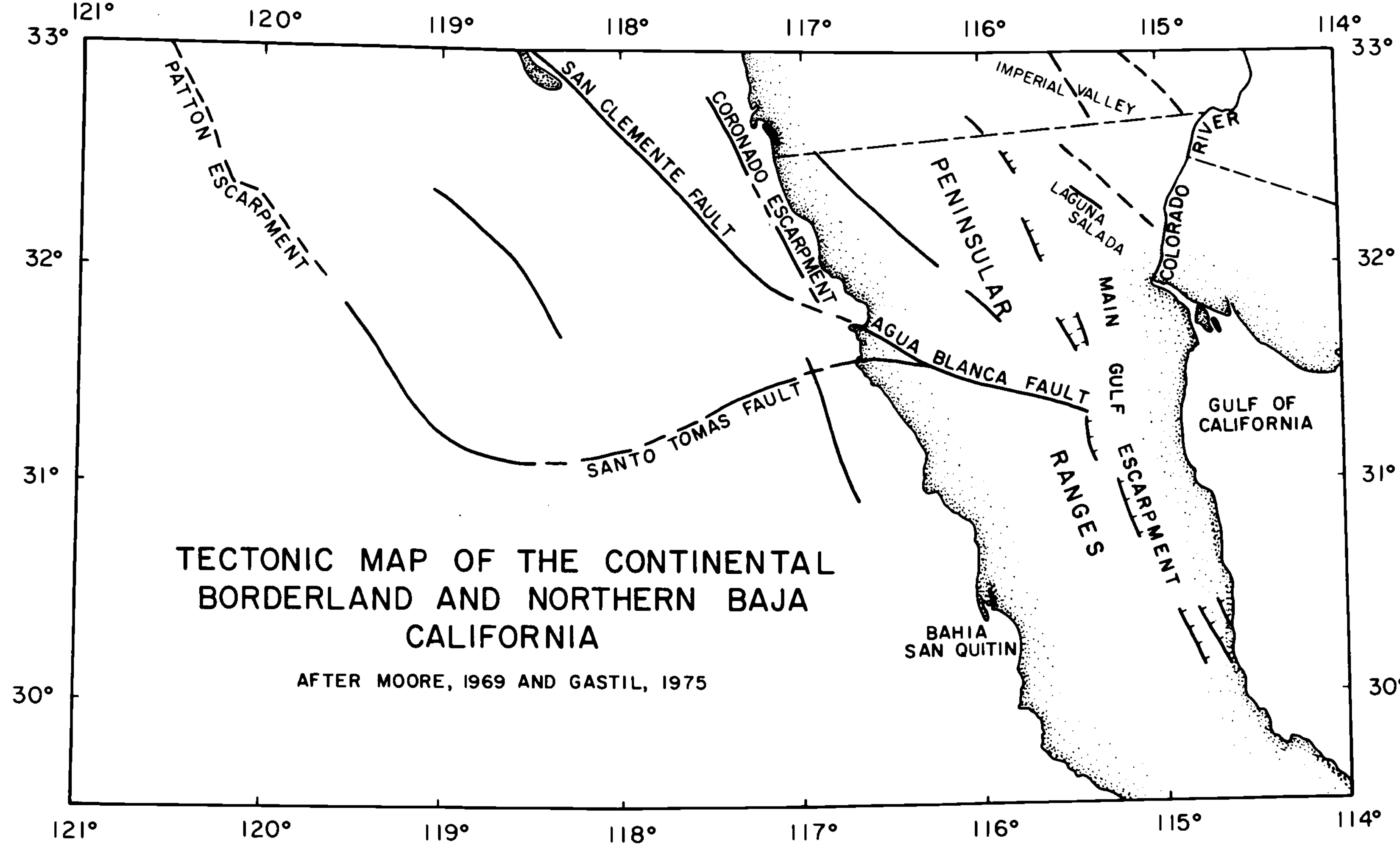


Figure 1. Tectonic map of the California Continental Borderland and the adjacent portion of California and Baja California.

F. P. Shepard, K. O. Emery, and their students and colleagues conducted most of the early geologic work on the Continental Borderland. Most of this early work has been summarized in a book by Emery (1960). His detailed bathymetric chart of the region north of 31.3°N Lat. shows the overall bathymetric pattern to be a series of sub-parallel ridges (or "banks") and basins which trend northwest-southeast. Some of the major ridges are the Tanner, Cortes, Sixty-mile, and Fortymile Banks. The most prominent basins in the area of this study are the East and West Cortes Basins, Velero Basin, and San Clemente Basin (Figure 2).

Emery (1960) also published a fault map and a geologic map of the region. Based mostly on physiographic expression he inferred a series of major faults which parallel the general topographic trend of the region and numerous minor faults at various angles to the major trend. Among the major faults he mapped is one along the base of the Patton Escarpment at the western edge of the region, and one along the Coronado Escarpment at the eastern edge. He also noted a major fault along the east side of San Clemente Island.

Emery's geologic map and description was based on physiography, rock outcrops on islands, and scattered bottom samples. He indicated that banks are underlain by a wide variety of igneous, sedimentary, and metamorphic rock types. The igneous rocks are predominantly basalt and andesite. The sediments include

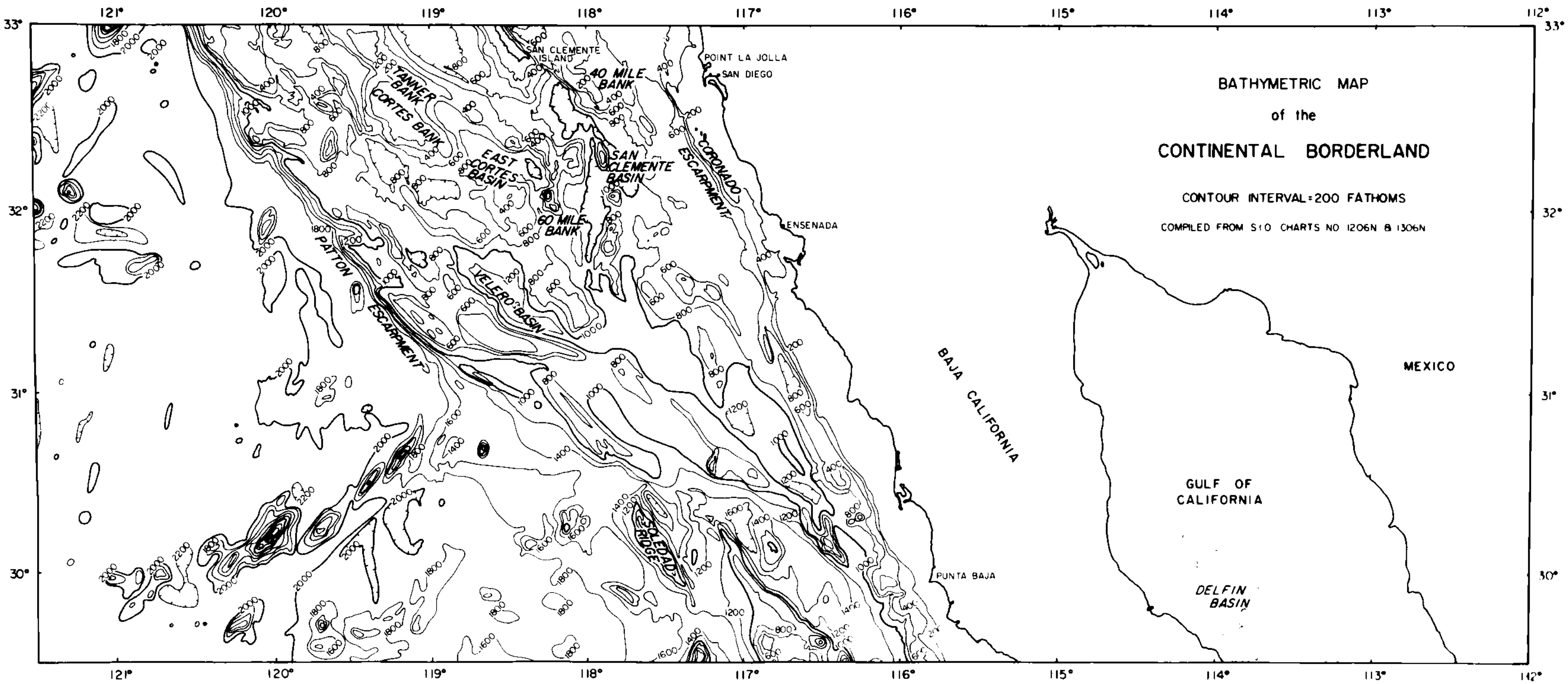


Figure 2. Bathymetric map of the California Continental Borderland.

mudstones, limestones, chert and conglomerate. They range in age from Jurassic to Pleistocene, though the majority are Miocene in age. The metamorphic rocks include gneiss, quartzite and glaucophane schist. The stratigraphic sequence of the metamorphic rocks is not clear. Emery noted the similarity of the metamorphic rocks to the onshore Franciscan complex and the Catalina Schist of the channel islands, and suggested that they are correlative. The basins are floored by thick sediments that are of recent age, at least at the surface. He suggested that the bank and basin structure began to develop in middle to late Miocene time.

Krause (1965) mapped the bathymetry between $27.75^{\circ}$ and $33^{\circ}$N Lat. He found that the same general pattern of northwest-southeast trending basins and banks continued to the south. Based on bathymetry and magnetic anomalies he mapped several faults in the area. One of these extends from Islas Los Coronados south-southeast to Bahia Todos Santos where it connects with the Agua Blanca Fault (see below). He also noted the offshore continuation of the Santo Tomas Fault (see below) which trends west-southwest across the Borderland, nearly at right angles to the main structural grain of the region. He noted that the bathymetry is about 450 m deeper on the south side of this fault, and based on apparent offsets of bathymetric features he concluded that the fault had a left lateral offset of about 15 km.

Moore (1969) published a large number of single channel seismic reflection profiles of the region and compiled a more detailed bathymetric map of the area described by Emery (1960) and Krause (1965). The reflection profiles enabled him to pick out numerous faults not found by previous workers, and also to demonstrate the presence of anticlines and synclines within the sedimentary section. The resulting structural map he published is much more detailed than those of previous workers, but the main features are much the same.

Vedder et al. (1974) published a report on the geology of the Borderland north of 32°N Lat. This report includes a geologic map which is based on numerous bottom samples and seismic reflection profiles. This map shows the distribution of rock types in greater detail than the geologic map of Emery (1960).

Atwater (1970) examined the pattern of magnetic anomalies in the northeast Pacific. She noted that no active spreading ridge exists between the mouth of the Gulf of California and the Mendocino Fracture Zone. Furthermore the oceanic crust in this region becomes older westward from the continent. She suggested that a subduction zone had once existed along this region and that the spreading ridge had been subducted under the continent in Miocene times. Because there is a right lateral component of motion between the North American and Pacific plates the motion along the continental margin must have changed from oblique subduction to strike slip. This motion is now largely taken up inland along the San Andreas Fault Zone, the Borderland and the onshore area west of the San Andreas Fault Zone having become attached to the Pacific plate. The idea that the San Andreas represents a rise-rise transform had been suggested earlier by Wilson (1965). Since the strike-slip motion must have originally been concentrated at the former subduction zone, Atwater believed that the complex structure of the Borderland may have resulted from the transfer of strike-slip motion inland to the present San Andreas system.

Taylor et al. (1971) measured magnetic anomalies in the region between 28° and 32°N Lat. They flew 12,000 km of tracklines in an east-west direction with tracklines spaced about 15 km apart. They found that anomaly 5B was the youngest detectable magnetic anomaly between 30° and 32°N Lat. According to the revised geomagnetic time scale for the Miocene (Blakely, 1974) the oceanic crust under this anomaly must be approximately 15 million years old. According to Atwater (1970) the age of the crust under this anomaly must indicate the time when the ridge was subducted under the North American plate.

The most comprehensive geologic study of the portion of Baja California adjacent to the Continental Borderland is that of Gastil et al. (1975), who summarized previous work in addition to much new mapping of their own. Except where noted, the following discussion of the area west of the Gulf of California and the Imperial Valley is based on their publication (Figures 1 and 3).

The rocks of the northern portion of Baja California may be divided into two groups which are separated by an episode of batholithic intrusion during the Mesozoic. The prebatholithic rocks may be subdivided into three roughly linear belts which trend along the peninsula.

The westernmost belt is composed of graywacke, bedded chert, serpentinite, and glaucophane schist. Although not exposed on land in northern Baja California these rocks are believed to underlie much of the Continental Borderland offshore. As noted above, Emery (1960) dredged samples of similar rocks from the northern portion of the Borderland, also similar rocks outcrop above water on Catalina Island. Miocene sediments containing clasts of such rocks are present in the Rosarito Beach Formation at the northwest corner of the state of Baja California. Sedimentological data indicates that these clasts were derived from a source to the west, in the Continental Borderland. Doyle and Gorsline (1977) dredged samples of metagraywacke from the area just west of Bahia San Quintin. These rocks are lithologically similar to rocks that outcrop on Islas San Benito, Isla Cedros and the Vizcaino Peninsula (Cohen et al., 1963; Minch et al., 1976). The age of these rocks varies from Jurassic to Cretaceous.

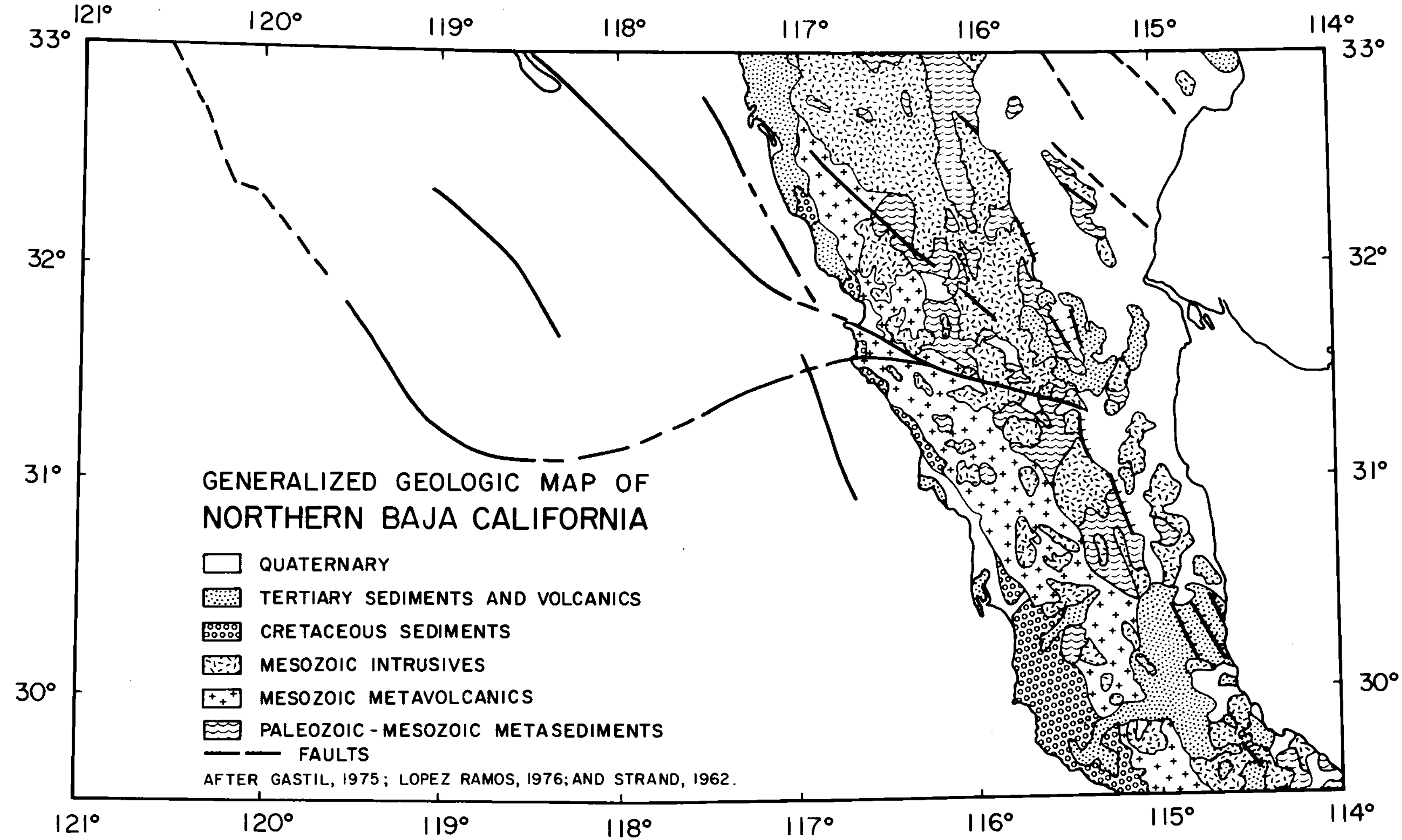


Figure 3. Generalized geologic map of northern Baja California.

Based on lithology, age and regional position it is generally believed that these rocks correlate with the Franciscan assemblage of California.

Onshore, to the east of the Franciscan-like rocks is a belt of Mesozoic metavolcanics and metasediments. The volcanic and volcanoclastic rocks are predominantly andesitic in composition but basalt and rhyolite are also present. Limestone, siltstone and mudstone are found with the volcanics. In general these rocks are metamorphosed to the greenschist facies. The eastern portion of this belt is predominantly shale and sandstone of Triassic and Jurassic age.

The easternmost belt of prebatholithic rocks is composed of metasediments of Paleozoic age. A wide variety of sediments are present but the rocks become increasingly carbonate rich to the east. These rocks were intruded in the Mesozoic Era when the Peninsular Ranges Batholith was formed.

The Peninsular Ranges Batholith is composed of numerous discrete intrusions which are largely granitic in composition (tonalite and granodiorite are the most common rocks) but gabbros are also present. The intrusives are in part contemporaneous with the metavolcanics discussed above. Potassium-Argon dates range from 107 to 60 million years before present, with younger rocks generally to the east. It is believed that the bulk of the plutonism occurred prior to 90 million years ago.

The post-batholithic rocks include Cretaceous to early Tertiary sediments which were derived from erosion of the batholith and deposited to the west. Volcanics and marine sediments were deposited in various areas in the Tertiary and Quaternary. Volcanic activity was greatest in Miocene time, but has continued virtually to the present time. Doyle and Gorsline (1977) report K-Ar ages as young as one million years for basalt dredged from the Soledad Ridge area.

The Agua Blanca Fault is a major east-west structure of the northern part of Baja California. It may be traced from the north side of Punta Banda with an overall trend of about S 70$^{\circ}$ E approximately two thirds of the way across the peninsula. It does not extend to the Gulf of California. As noted above, it can be followed offshore in the Borderland north to the Islas Coronado. The Santo Tomas Fault splits from the Agua Blanca Fault about 30 km east of Punta Santo Tomas. It extends westward to the coast at Punta Santo Tomas. As previously described, it can be followed offshore across the Borderland.

The east side of the Peninsular Ranges are a series of en echelon faults known as the Main Gulf Escarpment. The Gulf of California appears to be a graben-like structure which is down dropped relative to the Peninsula. Seismic refraction studies (Phillips, 1964) in the northern Gulf of California show a layer of sediments 3 to 4 km thick with velocities increasing with depth to about 4 km/sec. Beneath this is another layer about 3 to 4 km thick with velocities of 5 to 6 km/sec. Under the Gulf the main crustal layer has a velocity of about 6.7 km/sec. The depth to the mantle in the northern Gulf is not well known from seismic data but is at least 20 km. Thus it appears that the crust in the northern Gulf of California trough may be transitional between typical oceanic and continental crust. This is in contrast to the southern Gulf (south of 28°N Lat.) where velocities and structures are similar to those of the East Pacific Rise.

As noted before, it is generally accepted that the San Andreas Fault system is a transform fault along which there is right lateral motion between the Pacific and North American plates. Numerous workers (for example Larson et al., 1968) have suggested that the Gulf of California and Imperial Valley are not simple strike slip fault zones. Rather they are formed by a series of short, en echelon spreading centers linked by transform faults.

In the northern Gulf of California, Henyey and Bischoff (1973) propose that a spreading center exists at approximately 30°N Lat., under the Delphin Basin. Their interpretation is based on bathymetry and seismic reflection data which show a series of normal faults trending northeast-southwest in the Delphin Basin. Isla Angel de la Guarda is flanked by deep troughs which they interpret as transfrom faults. Preliminary heat flow data show that the Delphin Basin has a higher heat flow than the surrounding region.

Klitgord et al. (1974) measured magnetic anomalies in this area. They did not find linear anomalies which could be related to the geomagnetic time scale and which are typical of mid-ocean spreading ridges. However, the high rate of sedimentation due to the Colorado River may prevent the formation of highly magnetized pillow basalt, hence the lack of spreading type anomalies does not mean that a spreading center does not exist in the Delphin Basin.

To the north of the Gulf of California is the Imperial Valley. This valley seems to be a continuation of the Gulf of California structure which has been filled with sediments transported by the Colorado River. Based on seismic refraction and gravity data, Biehler et al. (1964) showed that sediments reach a maximum thickness of as much as 6 km under the center of the Imperial Valley. Elders et al. (1972) synthesized a wide variety of geophysical and geological data for the Imperial Valley. Using regional Bouguer gravity anomalies they determined that the mantle may be as shallow as 20 km beneath the axis of the trough. They noted that high heat flow, gravity highs, recent volcanism and incipient metamorphism of subsurface sediments were localized at the Buttes, Brawley, and Cerro Prieto. They concluded that local spreading centers are present in these places beneath the sedimentary fill. In support of this idea they showed that known movements determined by geodetic measurements along the Sand Hills, Imperial and other faults in the area are consistent with these faults being transforms linking the spreading centers. They then presented a model for the growth of the Imperial Valley. In the first stage, heating of the base of the crust is accompanied by rifting and upward expansion of the crust. As the rift develops it is rapidly filled by sediments from the Colorado River. Further extension results in basaltic intrusion into the base of the trough, ductile thinning of the lower crust, and hot rising brines which metamorphose the lower portion of the sedimentary fill. When the isotherms rise sufficiently, granitic basement rocks begin to melt, causing rhyolitic volcanism at the surface. In support of this process they note that the rhyolitic domes at the Buttes at the southern end of the Salton Sea contain xenoliths of basalt, metasediment, and partially melted granitic rocks.

# DATA SOURCES

## Free-Air Gravity Anomaly Data

Most of the free-air gravity data used in this study were obtained on magnetic tape from the National Geophysical and Solar-terrestrial Data Center (NGSDC) in Boulder, Colorado. In addition to this, data from several Oregon State University (OSU) cruises and from various published sources were used in compiling the final map (Figure 4).

The data from NGSDC were collected by the vessels USNS Shoup and OSS Surveyor in 1969 and 1970. The projects were "West Coast Gravity" conducted by NAVOCEANO (NGSDC file number 0078) and "California Continental Margin" conducted by NOAA (NGSDC file number 00130). Both vessels used satellite navigation systems. The measurements were originally reduced to gravity anomalies by use of the 1930 International Gravity Formula (IGF).

Several processing steps were done on the NGSDC data at OSU before the map was compiled. To make the data consistent with other OSU projects the data were converted to the 1967 IGF (International Association of Geodesy, 1971) by adding a correction factor delta to each point, where:

$$\text{delta} = 2.65 + [-13.695 + .135 \times \sin^2(\text{Lat})] \times \sin^2(\text{Lat})$$

The above formula also corrects for the 14.4 mgals reduction of the

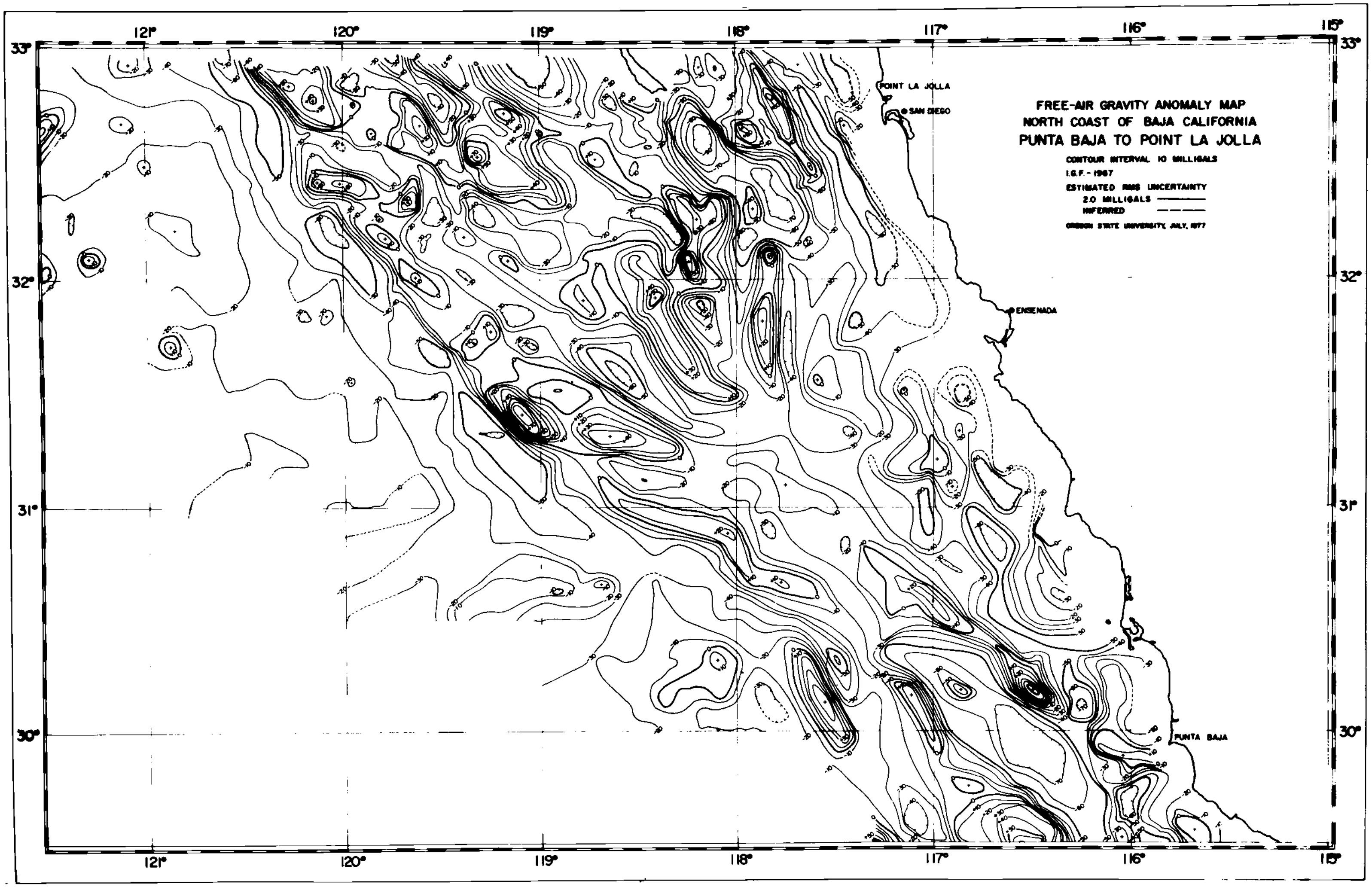


Figure 4. Free-air gravity anomaly map of the north coast of Baja California.

accepted value of absolute gravity at the Commerce Building Pier in Washington, D. C. (Morelli, 1971). All other stations in North America are referenced to this station. This was accomplished by use of the computer program NEWGRAV (Appendix). Data points were so closely spaced along the tracklines that computer plots of the data points were almost illegible. Before the final plots were made, every other data point was removed by using a computer program written by G. Connard (OSU). This still left a spacing of about .9 km between data points, the actual spacing being dependent on ship speed. Ship tracklines were in an east-west direction with a spacing of 18.5 km between tracklines. These were crossed at intervals of about 70 km by lines in a northeast-southwest direction (Figure 5).

The NGSDC free-air gravity data were supplemented with data from several other sources. The most important of these were the Baja 75 and Baja 76 projects. These cruises were joint ventures of the OSU Geophysics Group and the Direccion General de Oceanografia, Mexico. The data were collected aboard the Mexican research vessel DM-20 during the summers of 1975 and 1976. Other OSU data were from three cruises of the RV Yaquina (YALOC 7110, YALOC 7302, YALOC 7309) and one cruise of the RV Wecoma (WELOC 75). To the above trackline data were added submarine pendulum gravity stations from Worzel (1965) and land stations on the

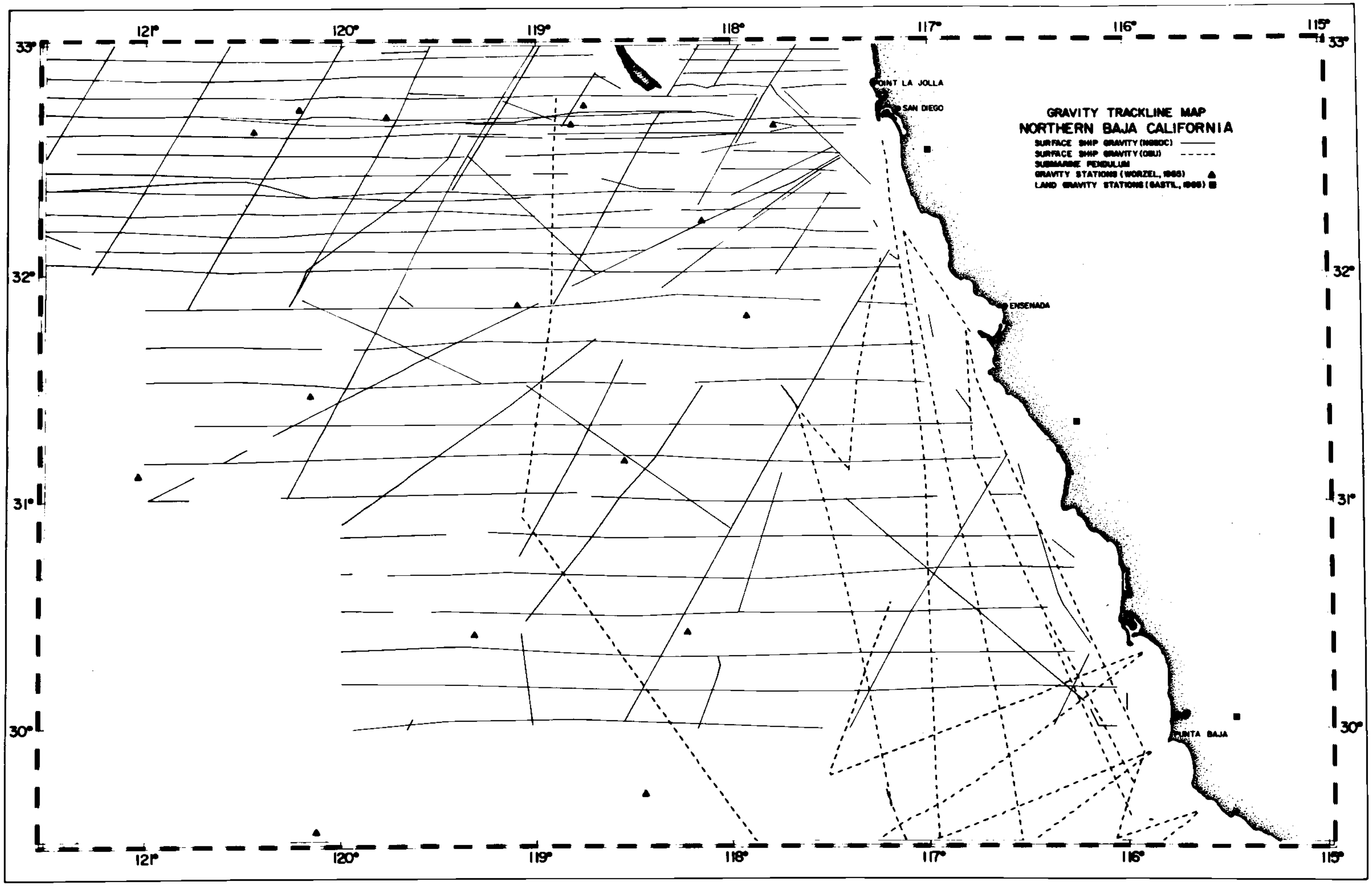


Figure 5. Location of free-air gravity measurements.

coast from Gastil et al. (1975).

All of the available data were plotted on a Mercator grid at a scale of 16 in/$^{o}$. The data were hand contoured with a contour interval of 10 mgals. The root-mean-square of trackline crossing errors for the complete data set was found to be 2.0 mgals. This gives a good measure of the overall uncertainty of the final contoured map.

## Bouguer Gravity Anomaly Data

Free-air gravity anomalies are very strongly influenced by terrain features. Because of the rugged and variable topography of the Continental Borderland a simple Bouguer gravity map was constructed (Figure 6). This is accomplished by computing the gravity due to an infinite slab of rock with thickness equal to the water depth and adding this to the free-air gravity anomaly at that point. This amounts to replacing the water with rock of assumed density of 2.67 gr/cc, and is in effect a first order terrain correction.

Water depth was not recorded at every gravity data point. In these cases a linear interpolation was made between the closest points on the trackline for which depth was recorded. This was done using computer program DEPINT (Appendix). Program FAATOSBA (Appendix) then computed the simple Bouguer gravity anomaly at each point. The data were then plotted and hand contoured at the same scale as the free-air gravity map. The root-mean-square crossing

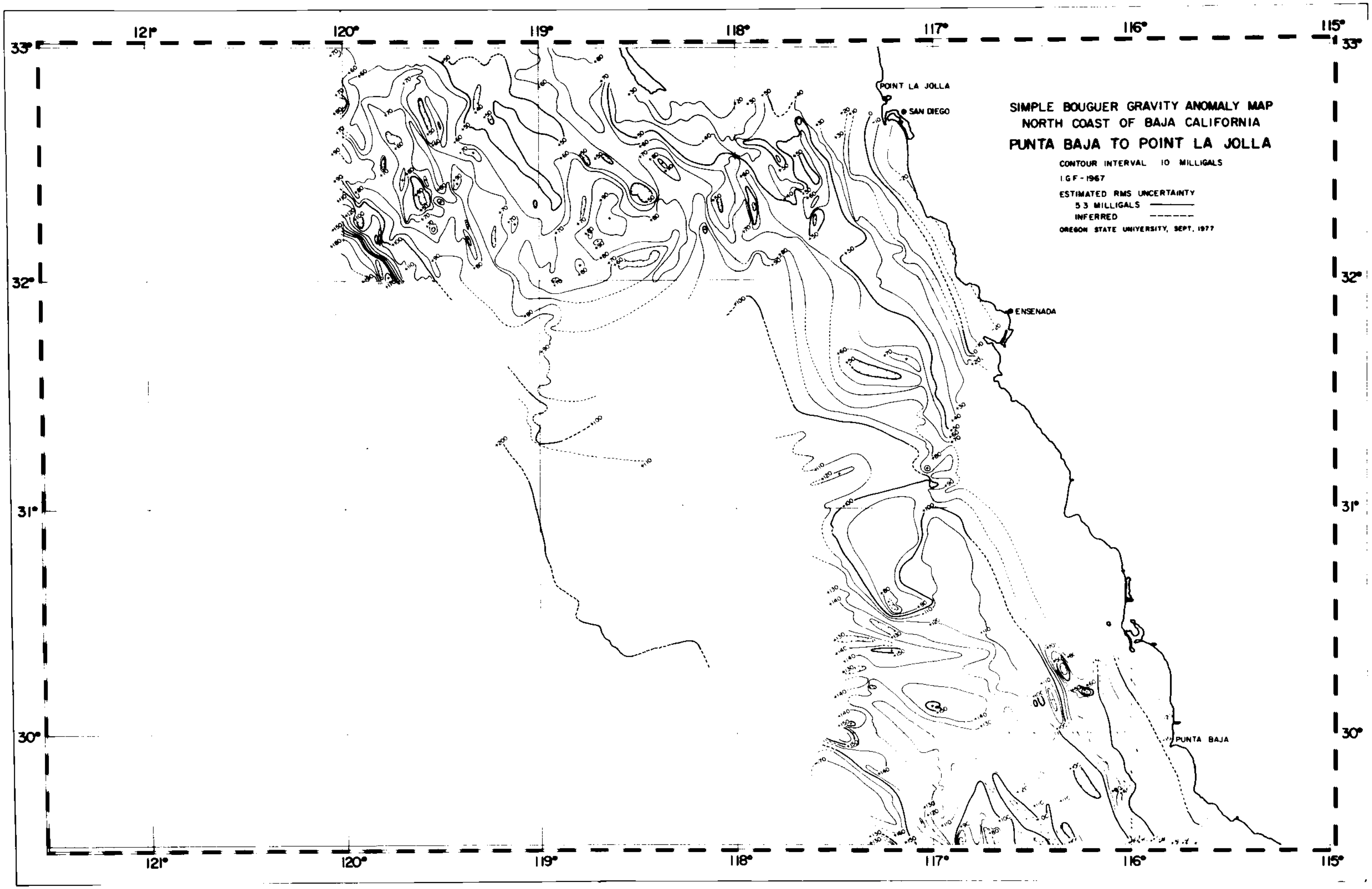


Figure 6. Bouguer gravity anomaly map of the north coast of Baja California.

error uncertainty is 5.3 mgals.

The data from NGSDC did not include any bathymetry at all for the area south of 32°N Lat. and west of 120°W Long. For these areas only the OSU data and the rather widely spaced pendulum gravity stations (Worzel, 1965) were available. Some areas of the map had no data at all and therefore could not be contoured.

## Magnetic Anomaly Data

Magnetic anomalies are found by subtracting a theoretical field value from the measured total magnetic field at each data point. The theoretical field used for this study is the 1965 International Geomagnetic Reference Field, or "IGRF" (Zmuda, 1971). The IGRF is a spherical harmonic series of 8 terms which represents the main geomagnetic field at any point in time and space. The coefficients for the series are determined by a least squares fit to measured data.

Regan and Cain (1975) discuss the use of field models in magnetic surveys. Ideally a field model will represent the magnetic effect of sources within the core. Any effects from non-crustal sources which are not represented by the IGRF will show up as pseudo anomalies on the final map. This can easily happen since the complexity of the field model is dependent on the maximum degree of the function used for the model. Also, errors can be introduced into the field model by uneven distribution in time and space of the data used to determine the coefficients of the function.

Figure 7 is a total magnetic field anomaly map of the area of this study. The trackline data from NGSDC and OSU which were used for the magnetic map are shown in Figure 8. Comparison of this map with other magnetic maps of the Baja Peninsula (Huehn, 1977; Calderon, 1978; Coperude, 1978) shows a distinct gradient from south to north, with the anomalies at the north being more negative than those to the south. This gradient extends over a great distance (at least 1300 km) and does not seem to relate to any geologic feature of the peninsula. This gradient is also present over oceanic crust west of the peninsula, where structures of a size sufficient to account for an anomaly of this wavelength are not known to exist.

The reasons noted above make it quite likely that the south to north gradient is not due to crustal and subcrustal structures but rather is an effect introduced by the IGRF. This interpretation is supported by the work of Regan and Cain (1975). They compared the eighth order IGRF with a thirteenth order field known as POGO. A map of the difference between the two fields shows a distinct gradient from south to north along the Baja Peninsula. In the region between 29° and 33°N Lat. the IGRF is negative relative to POGO. This is consistent with the effect observed on the magnetic maps.

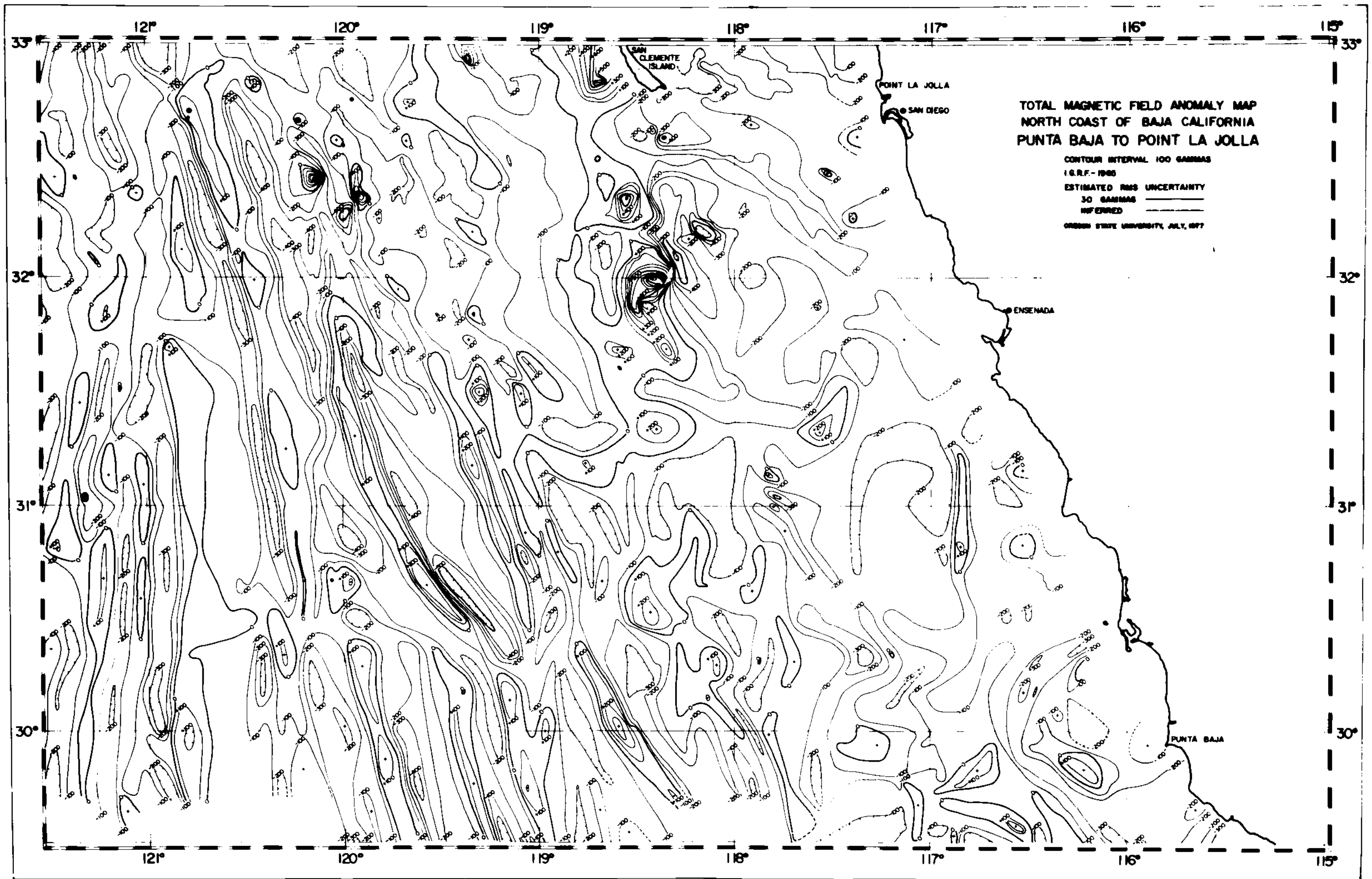


Figure 7. Total magnetic field anomaly map of the north coast of Baja California.

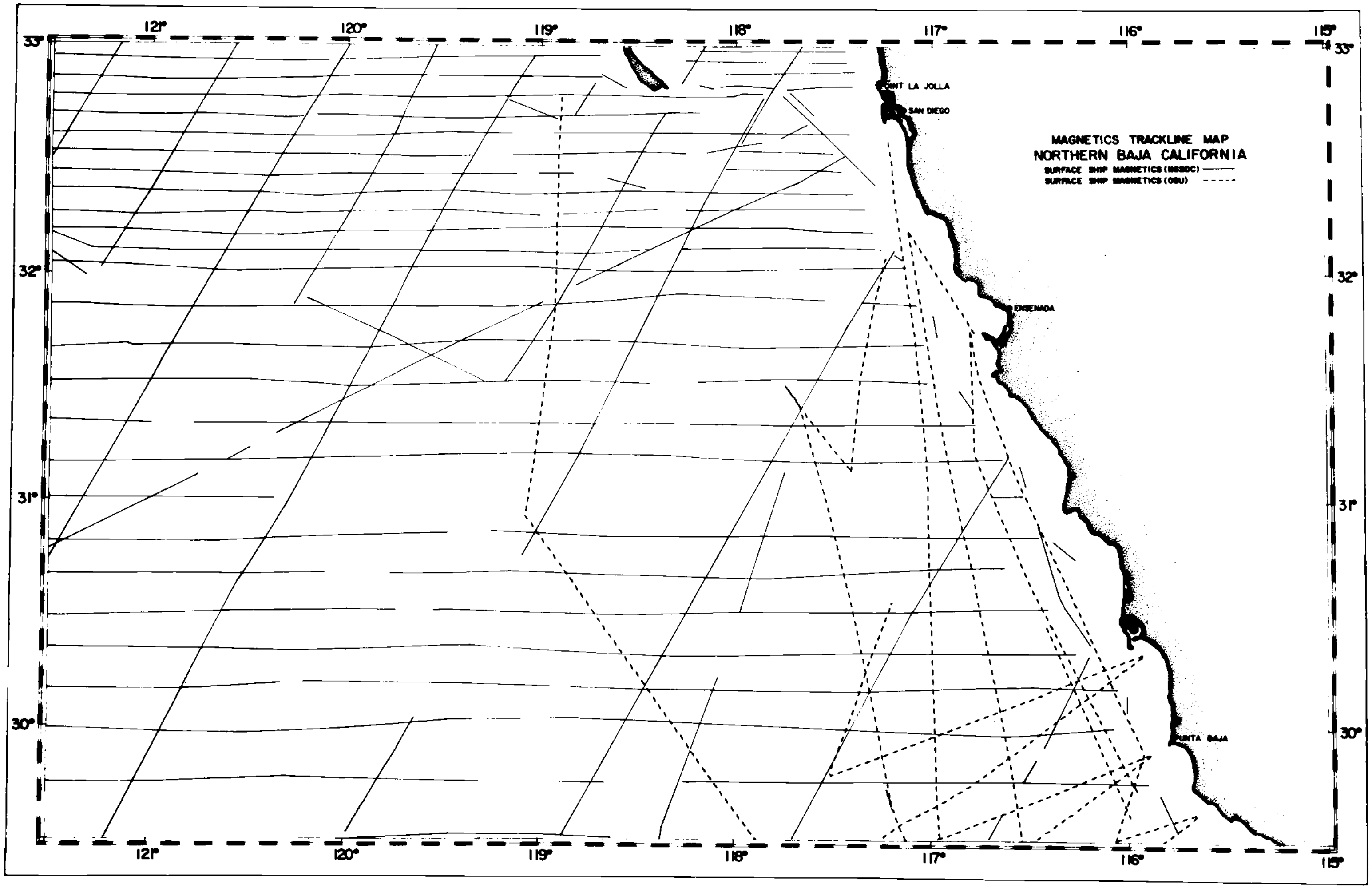


Figure 8. Location of magnetic field measurements.

# DATA INTERPRETATION

## Free-Air Gravity Map

The free-air gravity map (Figure 4) can be divided into two main regions. The southwestern portion of the map is characterized by broad anomalies with amplitudes generally between zero and -20 mgals. This area is a portion of the Pacific Ocean basin known as the "Baja California Seamount Province" (Menard, 1955). A number of small, isolated, positive anomalies are superimposed on the broad anomalies of this region. These smaller features are centered over various unnamed seamounts. The most conspicuous of these anomalies, which has a maximum amplitude in excess of +20 mgals, is located on the western edge of the map at 32.7$^{o}$N Lat.

The Continental Borderland, which includes all of the area east of the Patton Escarpment and the Soledad Ridge, has a very different gravity expression. This portion of the map shows a complicated pattern of closed highs and lows. In general this pattern follows the physiographic features of the Borderland, with gravity highs over ridges and lows over basins. The amplitude of these anomalies is much greater than in the region to the southwest. The gravity values range from a maximum in excess of +70 mgals over the Outer Ridge to a low of -90 mgals over the San Clemente Basin.

Of greatest geologic interest are those areas where gravity anomalies and bathymetric features are not clearly associated with each other. One such anomaly is the gravity low found along the base of the Patton Escarpment. The map of Vedder et al. (1974) shows that this feature begins north of the area of Figure 4. The gravity low extends south at least to 30.25°N Lat. South of this the feature becomes obscured by other trends. This anomaly has a low of -70 mgals at 33°N Lat. Throughout most of its length this gravity low does not correspond to any physiographic basin. One possible explanation is that the gravity low results from a buried trench-like structure at the base of the escarpment, filled with low density sediments. Another possibility is that the anomaly is due to a change in crustal structure at the edge of the Borderland. These possibilities will be discussed further in connection with the crustal models.

A small, roughly circular, closed gravity high is located at 32.5°N Lat., 119.3°W Long. at the west edge of Cortes Bank. Cortes Bank is separated by a slight depression about 100 m deep from Tanner Bank. The tops of these banks are fairly flat, and the gravity values over them average +40 to +50 mgals. The closed high is in excess of +70 mgals but is not located over any corresponding shallow point. A seismic reflection profile (Moore, 1969) indicates that Cortes Bank and Tanner Bank are sediments folded into anticlines. The gravity high indicates that higher density rock may be present at shallow depths under Cortes Bank. This could be either intrusive rock, or basement that has been faulted upward. The circular nature of the gravity high would suggest that intrusion, rather than faulting is the likely cause of the anomaly. This interpretation is supported by the work of Vedder _et al._ (1974), who dredged basalt from the flanks of Cortes Bank in the vicinity of this gravity high. However, their geologic map does show several small faults on the sides of Cortes Bank, so that a fault block origin of the gravity high cannot be ruled out.

An elongate positive anomaly with an average value of +30 mgals is located just east of Velero Basin at 31.75°N. Lat., 118.35°W Long. It is located over a very broad, unnamed ridge which forms the eastern side of Velero Basin. This ridge is underlain by folded and faulted sediments, as is shown by the seismic reflection profiles of Moore (1969).

It is significant to note that the axis of the gravity anomaly is located about 15 km west of the main topographic divide on the ridge. Furthermore, the amplitude and gradient of the anomaly are greater than one would expect over such a broad, flat topped feature. This evidence suggests that this anomaly is at least in part the result of high density rock either within or beneath the sediments. Basalt has been dredged from the southern end of the ridge, though not under the main gravity anomaly (Krause, 1965). Another possibility is that the ridge is underlain at shallow depth by Franciscan type rocks. These are known to outcrop nearby on Sixtymile Bank and another unnamed ridge to the east (Vedder et al., 1974). Both of these outcrops of Franciscan type basement rock have strong positive gravity anomalies associated with them. The geologic interpretation of this anomaly will be discussed further in connection with crustal model A-A'.

The most negative gravity anomaly on the map is -90 mgals, over the northern San Clemente Basin. The floor of this basin is roughly 1.1 km lower than the ridges on either side. The gravity anomalies over the ridges average close to zero. An order of magnitude calculation of the thickness ($\Delta z$) of sediment fill can be made using the infinite slab formula:

$$g = 2\pi\gamma(\Delta\rho)(\Delta z)$$

A seismic reflection profile (Moore, 1969) indicates the ridges on the northwest and southeast are probably basement or volcanic rocks. If we assume an average density contrast ($\Delta\rho$) of 1.6 gr/cc between the ridges and seawater then the effect due to the topographic basin is about 74 mgals. Assuming that the sediment density is roughly 2.0 gr/cc then about .6 km of sediment is necessary to account for the remaining 16 mgals of gravity anomaly. This is reasonable since the reflection profile shows a two way travel time of at least .75 sec. At a minimum (seawater) velocity of 1.5 km/sec this amounts to .56 km of sediment, which agrees closely with the gravity calculation.

## Simple Bouguer Gravity Map

The simple Bouguer gravity map (Figure 6) has an assumed reduction density of 2.67 gr/cc. The map shows an inverse correlation with topography. That is, topographic basins show Bouguer gravity highs and ridges show lows. Ideally a Bouguer gravity map should show little or no correlation with topography. The inverse correlation suggests that the reduction density of 2.67 gr/cc is too high. The terrain features have been over compensated by the addition of too much mass. The average density of the near surface rocks underlying the Borderland must be somewhat less than 2.67 gr/cc.

The west side of Cortes Bank shows a small closed gravity high. This is located in the same place as the positive free-air anomaly noted above. The fact that this area shows a Bouguer gravity high while the rest of Cortes and Tanner banks are gravity lows indicates that the density of the rocks under this area is greater than 2.67 gr/cc. This tends to support the earlier conclusion that the west side of Cortes Bank is underlain by either an intrusive mass or else a fault block of high density rocks.

The Bouguer gravity map shows a distinct difference between the northern and southern portions of the Borderland. North of about 31.3$^{\circ}$N Lat. the Bouguer anomalies are generally less than +100 mgals, except for the region within about 60 km of the coast. This is probably a topographic effect related to the deeper water south of the Santo Tomas Fault. Another possible cause would be a shallower mantle.

Within about 60 km of the coast the Bouguer anomalies are linear and trend parallel to the coast. The values decrease to -20 mgals in Bahia San Quinton, Bahia Todos Santos, and just south of San Diego Bay. These anomalies are quite consistent with those shown for this area on the Bouguer gravity map of Gastil et al. (1975).

## Total Field Magnetic Anomaly Map

The magnetic anomaly map (Figure 7) shows a distinct difference between the deep ocean to the west and the Continental Borderland. The oceanic crust shows a highly regular pattern of linear anomalies. At the west side of the map these anomalies trend almost exactly north-south. However, east of about 120.5°W Long. the trend changes slightly to the northwest. The location of these anomalies over the deep ocean and their distinctively linear nature almost certainly indicates that they are remnant anomalies resulting from reversals of the earth's field. This is confirmed by the work of Taylor et al. (1971). They found a systematic decrease in the apparent spreading rate with increasing latitude, from about 3.6 cm/yr at 30°N Lat. to 2.3 cm/yr at 32°N Lat. This accounts for the change in direction of the anomalies. The anomalies appear to be left laterally offset about 15 km at 30.4°N Lat. However, this offset does not extend westward past the relatively wide positive anomaly at 120.8°W Long. The profiles of Taylor et al. (1971) identify this as anomaly 6 which is about 21 million years old, according to the revised geomagnetic time scale of Blakely (1974).

The seamount chain that extends southwest across the lower portion of the map does not show up in the magnetic anomalies. The seamount chain is in the same vicinity as the offset anomalies previously noted. However the trend of the seamounts is to the southwest rather than due west as is the offset in the magnetic anomalies.

In contrast to the linear pattern of magnetic anomalies over the oceanic crust, the Continental Borderland exhibits a very irregular, nonlinear pattern. In addition, the Borderland anomalies have a distinctly longer average wavelength than those to the west. The transition from oceanic to Borderland anomalies occurs over the Patton Escarpment. However, there is no single continuous magnetic anomaly associated with the Patton Escarpment, in spite of the fact that it is the longest and most prominent topographic feature in the area of this study. The Soledad Ridge is another very prominent topographic feature which does not have a distinct magnetic signature. The long wavelength and lack of correlation with topography of the Borderland anomalies suggests that they result from deep crustal sources.

An exception to this is the very prominent magnetic anomaly located east of the Velero Basin at 32°N Lat., 118.4°W Long. This anomaly has an amplitude of +1100 gammas, which is by far the highest of any on the map. This anomaly is in the same location as a free-air gravity anomaly noted in a previous section, and probably results from the same structure. The southern extension of this anomaly is crossed by crustal section A-A', and possible geologic explanations for the anomaly will be discussed below.

As previously noted, Krause (1965) studied the magnetic anomalies of a portion of the Borderland. He noted on his map the presence of an anomaly near the edge of the Borderland north of 30°N Lat. He suggested that this anomaly might represent an extension of a fault zone that outcrops to the south on Isla San Benito. This anomaly is not found on Figure 7. In fact, a careful comparison with the map of Krause shows that the anomalies in this area on Figure 7 are short, irregular, and for the most part trend at different angles than this supposed fault zone. Therefore, the data presented on Figure 7 do not support a northward extension of the San Benito Fault Zone.

There are several possible explanations for this discrepancy between the two maps. As noted above, most of the data for Figure 7 were collected using satellite navigation. Krause's navigation was by celestial and shore fixes. He estimates his navigation uncertainty as ±1 mile. The estimated RMS uncertainty of Figure 7 is 30 gammas. Krause gives no estimate of uncertainty for his magnetic data, however, because of the method of navigation it is certainly no better than that of Figure 7 and probably worse. Yet his contour interval is only 50 gammas. Finally, he seems to have contoured anomalies considerably smaller than his trackline spacing. He states that "Where the anomaly was obviously related to some bathymetric feature, the anomaly was drawn compatible to that feature..." (Krause, 1965, p. 630). Figure 7 was contoured only by interpolation between known values, with no assumptions about the relationship of magnetic anomalies to bathymetric features. This is not to imply that Krause's map, or all conclusions based on it are entirely wrong. In most other areas the maps are in reasonable agreement with regard to major anomalies.

# CRUSTAL MODELS

Figure 9 shows the location of crustal and subcrustal cross sections A-A' (Figure 10), and B-B' (Figure 11). These sections are modeled with the assumption that the geologic structures can be approximated by polyhedrons which are infinite in the direction normal to the cross section. This assumption permits the calculation of gravity anomalies by the method of Talwani et al. (1959). This was accomplished by use of computer program GRAV2DLD (Huehn, 1977). The two dimensional assumption also permits the magnetic anomalies to be calculated by computer program TWOMAG (Huehn, 1977) using the method of Talwani and Heirtzler (1964).

As noted previously, the magnetic anomalies are too negative in this region due to the IGRF used in data reduction. In order to directly compare the computed anomalies with the mapped anomalies, a value of 125 gammas was subtracted from the computed anomalies. This is equivalent to adding 125 gammas to the measured anomalies.

The models are developed by successive iterations until the computed gravity and magnetic anomalies are in agreement with the observed anomalies. The models are also made consistent with available seismic refraction, seismic reflection, bathymetry, and surface geologic data.

In order to directly compare observed anomalies with the

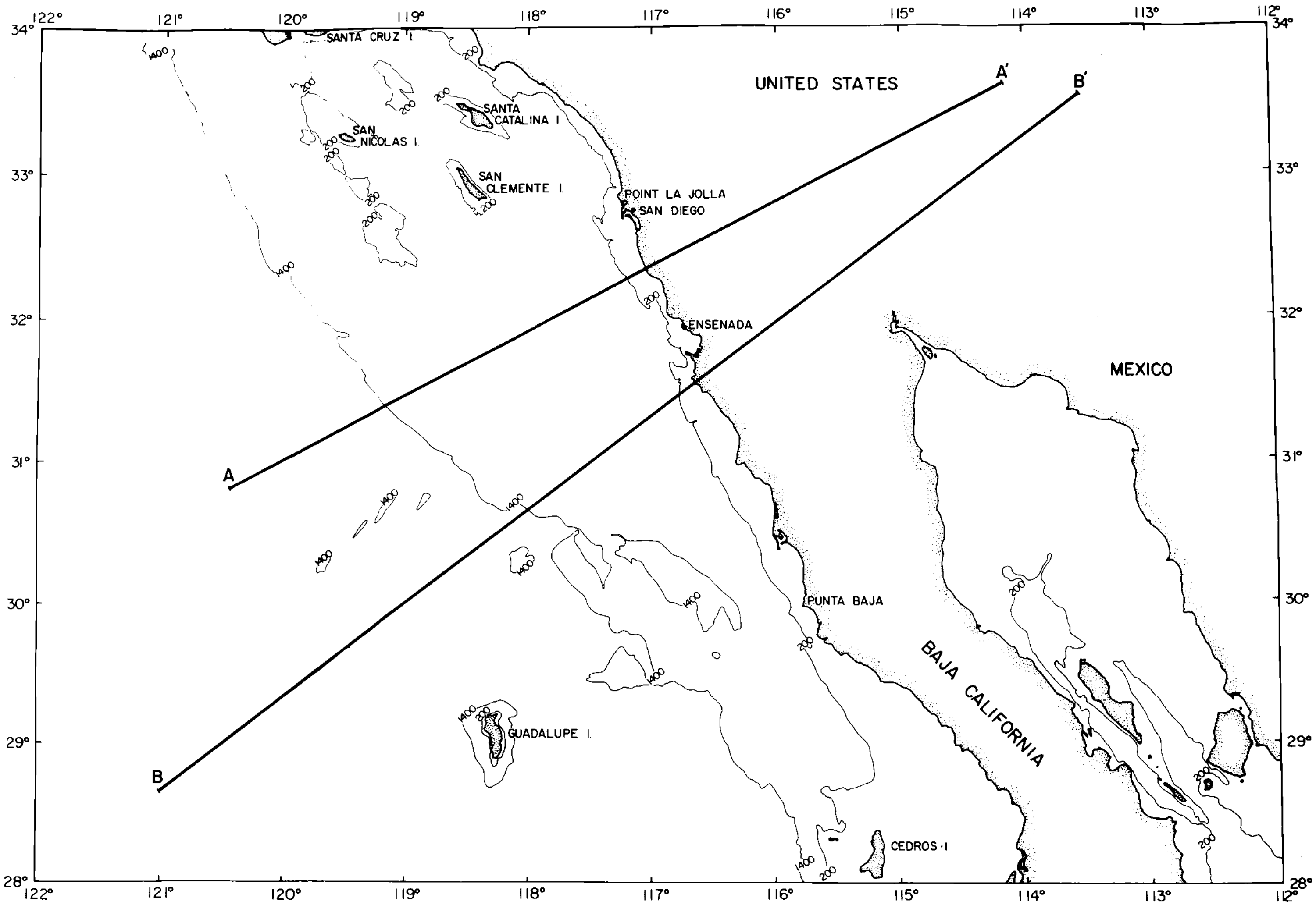


Figure 9. Location of crustal and subcrustal sections, and geologic cross sections.

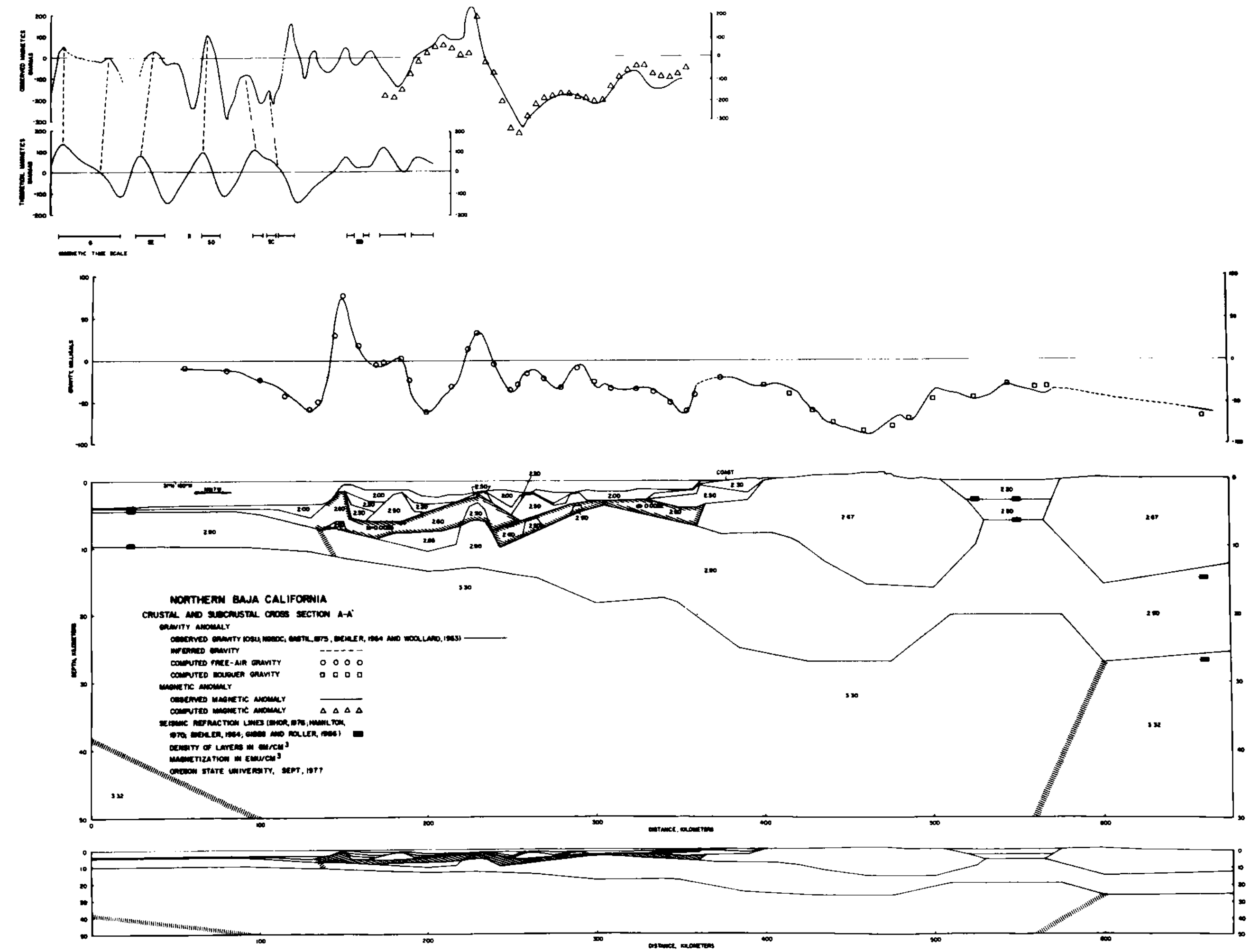


Figure 10. Crustal and subcrustal section A-A'.

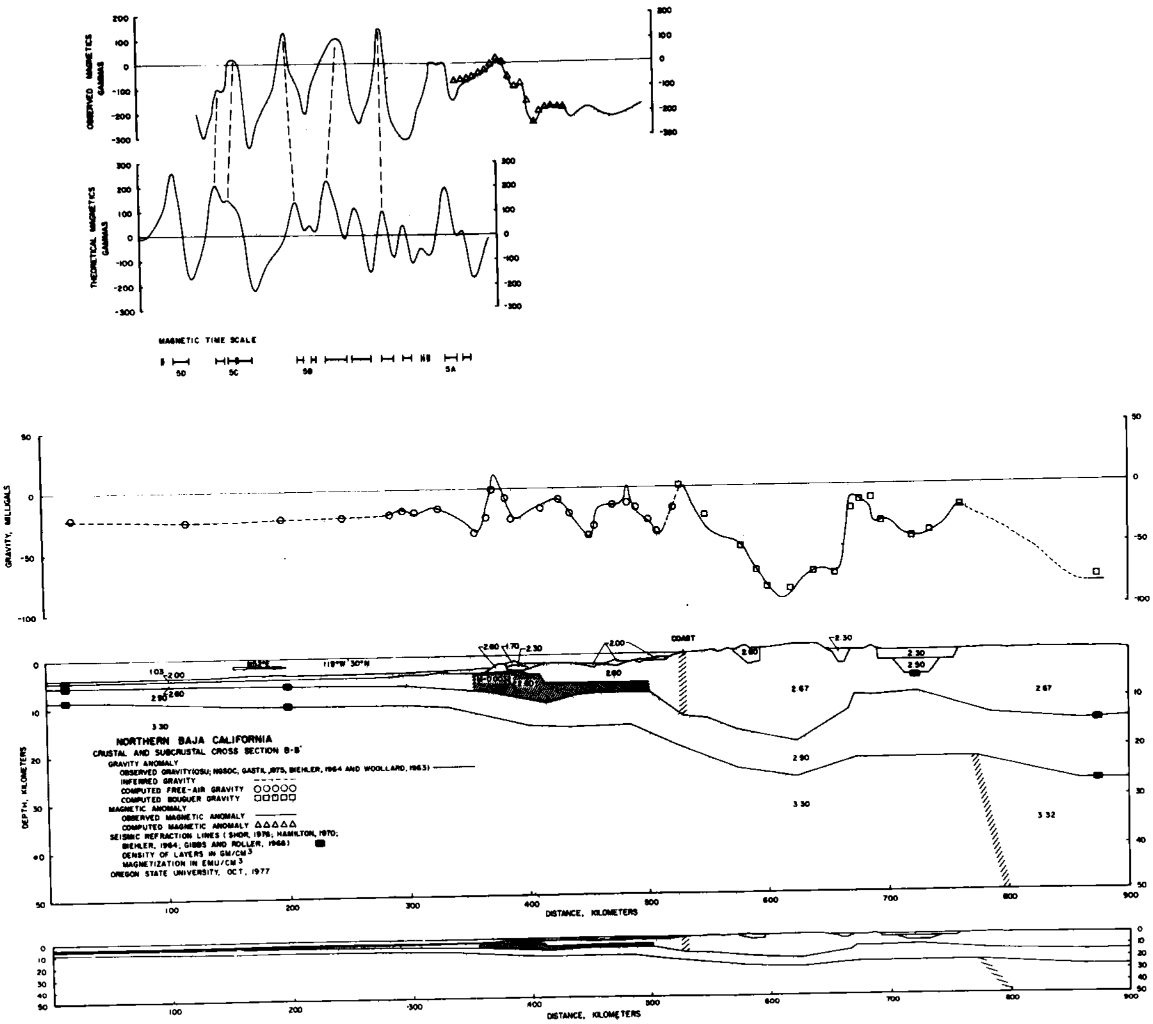


Figure 11. Crustal and subcrustal section B-B'.

gravity computed from a model it is necessary to subtract from the model gravity the gravitational effect of a standard section. The standard section is assumed to have a zero anomaly. This is analogous to subtracting a theoretical value from an observed gravity value to obtain an anomaly. The standard section developed by Barday (1974) was used for this purpose.

The anomalies computed from the model are compared with observed free-air gravity anomalies at sea and simple Bouguer gravity anomalies on land. The use of Bouguer gravity anomalies requires that all rocks above sea level must be modeled with a density equal to the actual density minus 2.67 gr/cc. This is due to the fact that the Bouguer correction has already removed the effect of above sea level rocks with an assumed density of 2.67 gr/cc.

Section A-A' is across the northern Borderland, just north of and approximately parallel to the Santo Tomas Fault. The location and orientation of the section is chosen to cross an area where the gravity and magnetic anomalies, and the bathymetry can be reasonably modeled as a two dimensional structure. The line chosen crosses several of the most interesting features of the Borderland. These include the gravity low at the base of the Patton Escarpment, the Outer Ridge gravity high, and the large gravity and magnetic anomaly east of the Velero Basin. The landward end of the section crosses the Peninsular Ranges and the Imperial Valley. Within the Imperial

Valley the section goes directly across the Brawley geothermal anomaly.

The gravity profile on section A-A' is obtained from Figure 4 for the offshore portion and from the Bouguer gravity maps of Gastil et al. (1975), Biehler et al. (1964), and Woollard and Rose (1963) for the onshore area. Topography is from the bathymetric chart of Moore (1969), the 1:500,000 contour maps of the Comision Intersecretarial Coordinadora del Levantamiento de la Cartografica de la Republica Mexicana (1958), and 1:250,000 contour maps from the U.S. Geological Survey. The magnetic data for the area east of the 100 km mark are projected onto section A-A' from a trackline which is parallel to and north of the section.

The seaward end of A-A' is constrained by seismic refraction data obtained from the Hilo 2 shot (Shor et al., 1976). Refraction data in the Imperial Valley is from Hamilton (1970) and Biehler et al. (1964). The refraction tie at the east end of A-A' is from Gibbs and Roller (1966). This tie is projected into A-A', along a line parallel to the geologic structure, from a location 175 km to the north. Seismic reflection data from Moore (1969) is used to indicate offshore areas underlain by sedimentary basins.

The densities in the oceanic crust at the west end of section A-A' are from the standard section of Barday (1974). Densities under the landward end are chosen from seismic velocities using the empirical relation between seismic velocity and density of Ludwig, Nafe, and Drake (1970), and from surface geology. These densities are adjusted where necessary to achieve a good fit to the data. Choosing densities for the complex geology of the Borderland is a more difficult problem. The refraction line of Shor and Raitt (1958) shows a velocity of 5.1 km/sec at shallow depths under the Patton Escarpment. The geologic map of Vedder et al. (1974) shows Franciscan rocks outcropping in this region. Similar rocks are known to be present under at least part of section A-A'. Therefore, using the Ludwig, Nafe, and Drake relation a density of 2.6 gr/cc is indicated for the basement rocks of the Borderland. Where necessary, this is modified to 2.5 gr/cc in order to better fit the gravity data. The surficial sediments are assumed to have a density of 2.0 gr/cc, the same as the sediments on the oceanic crust to the west. In the deeper basins the density of the lower layers of sediment is increased to 2.3 gr/cc to take into account the effects of compaction.

The basement is assumed to have a magnetization of .0032 emu/cc in the eastern portion of the Borderland. In the western portion it is necessary to increase the magnetization to .0055 emu/cc to achieve a good fit with the observed magnetic anomalies. In several places it is assumed that the upper portion of the 2.9 gr/cc layer is also magnetic. Several short wavelength magnetic anomalies located between 100 and 175 km are not modeled. A calculation using the half-width method (Grant and West, 1965, p. 326) indicates that the sources of these anomalies are only about 3 km deep. This suggests that the magnetic anomalies probably result from dikes intruded at very shallow depths within the sedimentary section.

The crustal section indicates that under the oceanic crust at the west end of section A-A' the mantle is at a depth of 9.7 km. The depth to the mantle gradually increases to about 13 km at a point half way across the Borderland. East of this the Moho deepens in a somewhat irregular manner and reaches a maximum depth of 27 km beneath the Peninsular Ranges.

Section A-A' shows the Moho to be 20 km below sea level under the Imperial Valley. This compares with an estimated depth of 21 km in this area which was obtained by Elders et al. (1972) using a two layer gravity model. Also, the seismic refraction studies of Gibbs and Roller (1966) included three seismograms recorded in the Imperial Valley. These records show Pn arrivals which are earlier than expected, based on arrivals at the other stations. If these time differences are due to thinning of the crust rather than velocity changes then Gibbs and Roller calculate that the mantle is at a depth of about 20 km under the Imperial Valley. Finally, Phillips (1964) reported mantle depths of 18.4 km and 23.4 km for two seismic refraction lines in the northern Gulf of California.

The hachured boundaries between density blocks in the mantle are to indicate that the change in density is probably gradational in character. The density of 3.32 gr/cc at the west edge of the section is from the standard mass column of Barday (1974). The transition back to 3.32 gr/cc at the eastern edge of the section is necessary to make the computed section agree with the seismic refraction data and the observed gravity. There is still some difference between the computed section and the seismic refraction data. However, the refraction station is located to the north where gravity is about 20 mgals more negative. If the structures on section A-A' were constrained to exactly fit the seismic refraction data then the computed gravity would be about 20 mgals less over the refraction station. Therefore, allowing for the difference in observed gravity, the east end of section A-A' is in reasonable agreement with the seismic refraction data.

Crustal models across the central and southern Gulf of California (Calderon, 1978; Coperude, 1978; Huehn, 1977) show a low density (3.15 gr/cc) upper mantle under the Gulf. This low density zone is necessary to fit the combined gravity and seismic refraction data. No such low density zone is required to fit the data on section A-A'. This difference in upper mantle density is consistent with the seismic refraction data of Phillips (1964). His profile down the length of the Gulf of California indicates mantle velocities of 8.2 to 8.3 km/sec under the northern Gulf, decreasing to 7.5 to 7.9 km/sec under the southern Gulf. The lower seismic velocities would suggest a lower density upper mantle in the southern part of the Gulf.

Section A-A' shows a number of significant features in the Borderland area. The gravity low at the base of the Patton Escarpment is partly the result of a trench-like depression which is filled with 2 km of sediments. The change in crustal structure at the edge of the Borderland also causes part of the gravity low. The Outer Ridge is a block of basement rock of density 2.6 gr/cc with a cap of lighter sediments. East of the Outer Ridge, at about 150 km, is a basin filled with about 4.5 km of sediments. This is separated from the Velero Basin which lies to the east by a ridge of dense (2.5 gr/cc) but relatively nonmagnetic material. The Velero Basin itself is filled with 2 to 2.5 km of sediments.

East of the Velero Basin, at 225 km, is a small ridge over which there are very large gravity and magnetic anomalies which were noted in the discussion of the gravity and magnetic maps. The crustal section indicates that this ridge is underlain by a very broad basement high which rises to within a few hundred meters of the sea-floor. This basement high is magnetic and has a core of very dense (2.9 gr/cc) material. This high density material is also present, though on a smaller scale, under several other basement ridges on this section.

At about 300 km across the section the magnetic layer thins to

.7 km. The layer under this is 2.9 gr/cc at a depth of only 3.7 km. It would be possible to fit the gravity data without raising the 2.9 gr/cc layer to this level. To do this it would then be necessary to raise the mantle to a shallower level. However, a seismic refraction profile of Shor and Raitt (1958) shows a mantle depth of about 24 km under the San Diego Trough, about 80 km north of A-A'. This refraction profile would project into A-A' at approximately the area where the magnetics indicates the thin upper crust. Section A-A' shows the mantle to be about 18 km deep in this area. Therefore, to fit the gravity without raising the 2.9 gr/cc layer to shallow levels would require an even greater discrepancy between the extrapolated seismic refraction data and the gravity section.

Under the Coronado Escarpment, about 15 km west of the coastline, the model cross section shows an abrupt lateral density change between sediments of 2.3 gr/cc on the west and 2.5 gr/cc rocks to the east. This tends to support the conclusion of Krause (1965) that a fault zone runs along the Coronado Escarpment.

The section shows 6 km of sediments lying directly upon dense (2.9 gr/cc) rock in the Imperial Valley. The 2.67 gr/cc rock, interpreted as granitic crust, does not appear to be continuous across the Imperial Valley in this area. The lower portion of the sedimentary fill is quite dense (2.5 gr/cc), and is probably somewhat metamorphosed. Metamorphism of sediments has been observed in drill cores from this area (Elders et al., 1972).

The magnetic anomalies over the oceanic crust at the west end of section A-A' are compared with theoretical anomalies which are computed with program THEOMAG (Lu and Keeling, 1974; Huehn, 1977) using a spreading rate of 3.0 cm/yr. The fit is not very good. However, by using the profiles of Taylor et al. (1971), anomaly 6 can be clearly identified on the magnetic anomaly map. Anomaly 6 then serves as a reference to identify the other anomalies. The model indicates that anomaly 5C is the youngest anomaly which can be clearly distinguished on section A-A'. This indicates that the crust west of the Borderland is about 16.5 million years old, according to the revised time scale of Blakely (1974). Taylor et al. (1971) suggested that anomaly 5B (15 m.yr) is also present, but this seems questionable, at least in the vicinity of A-A'.

Section B-B' (Figure 11) was chosen to be along a line south of the Santo Tomas Fault. Like section A-A' the exact location and orientation were picked in order to permit use of the two dimensional modeling technique. The gravity data were obtained from the same sources as for section A-A. The magnetic data were obtained entirely from Figure 7.

The offshore refraction ties are the Hilo 3 and Fanfare 5 lines reported by Shor et al. (1976). Both of these ties have been projected to section B-B' from the north a distance of about 120 km. The refraction tie in the Colorado Delta is a minimum depth to basement from Biehler et al. (1964) which has been projected into the section from approximately 25 km to the north. The easternmost refraction tie is from Gibbs and Roller (1966), as in A-A'.

Section B-B' shows the Moho to be at a depth of 8.5 km under the deep ocean to the west. The Moho deepens to a depth of about 15 km beneath the Borderland. Near the coast the Moho dips landward and reaches a maximum depth of 26 km under the Peninsular Ranges. The mantle then rises to within 22 km of the surface beneath the Colorado Delta. East of the Colorado Delta the top of the mantle is approximately 27 km below sea level. The density transitions in the mantle are similar to those under section A-A'. The transition from 3.32 gr/cc to 3.30 gr/cc mantle is located west of the west end of B-B'. The structure based on the gravity data east of the Imperial Valley fits the seismic data reasonably well using a mantle density of 3.32 gr/cc.

The sediment filled trough or trench at the base of the Patton Escarpment, noted on section A-A', does not appear to be present on section B-B'. The sediment at the base of the westernmost escarpment of the southern Borderland is about .9 km thick, only a few hundred meters thicker than on the oceanic crust to the west. The outer escarpment itself, located at 375 km on section B-B', is composed of relatively nonmagnetic basement rocks.

Just east of the westernmost escarpment is a ridge of very low density (1.7 gr/cc) sediments underlain by a basin. The very low density of these sediments is required to fit the observed gravity anomaly. However, the topography of this ridge does not fit the two dimensional assumption very well because the ridge narrows abruptly just south of the line of section B-B'. This suggests that the low sediment density is at least partially an artifact of the two dimensional modeling technique. Between 410 km and the coast section B-B' shows only a few small basins with less than 1 km of sediment fill. A sediment filled basin at 470 km is located beneath a small ridge.

The magnetic anomalies indicate that in general only the lower portion of the 2.60 gr/cc layer is magnetic. The magnetic block is not as irregular in shape as on section A-A'. It is not necessary to use any magnetization other than .0032 emu/cc to fit the anomalies. No magnetic structure is shown east of 440 km because the anomalies in this area trend parallel to the line of section B-B' and therefore are not suitable for two dimensional modeling.

The remnant magnetic anomalies over the oceanic crust are compared with theoretical anomalies by use of the same technique described for section A-A'. The comparison indicates that the youngest anomaly which can be identified is between anomalies 5B and 5A. This means that the youngest oceanic crust in this area is about 13.5 million years old, according to the geomagnetic time scale of Blakely (1974).

East of the coast, at 580 km the section crosses a belt of gabbroic plutons within the Peninsular Ranges. This is modeled with a block of 2.80 gr/cc. At 650 km the section crosses the Laguna Salada, which is a fault controlled basin with about 2.5 km of sediments. The upper crust thins abruptly at this point. However, in contrast with section A-A', the granitic crust appears to be continuous beneath the Colorado Delta. This trough is filled with 5 km of sediments. The lower portion of this sedimentary fill has a high density of 2.5 gr/cc which is probably the result of metamorphism, as is observed in samples from drill cores (Elders _et al._, 1972).

# GEOLOGIC INTERPRETATION

Figures 12 and 13 are geologic interpretations of sections A-A' and B-B' respectively. As noted previously, geologic data indicate the presence of Franciscan type rocks in numerous parts of the Borderland. The gravity models indicate that much of the Borderland is underlain by rocks with densities in the range of 2.5 to 2.65 gr/cc. This is within the range expected for metavolcanics, metagraywacke, and serpentinite rocks such as are found in the Franciscan (Cady, 1975; Stewart and Peselnick, 1977; Birch, 1960). The geophysical models are therefore consistent with and interpreted as a thick section of Franciscan rocks offshore.

The geophysical sections provide very little information about the exact location or nature of the contact between the Franciscan and the oceanic crust on the west and the crystalline complex on the east. This is because there is no large contrast in densities between these rocks. Also, there is a gap in the data between the offshore and onshore areas. The broken contacts on the geologic interpretations indicate this uncertainty, and are not meant to imply anything about the actual nature of the contacts.

The actual geology is almost certainly more complex than Figures 12 and 13 indicate. Post-Franciscan volcanics are present in the Borderland and are no doubt included in the areas interpteted as Franciscan and sedimentary rocks. The magnetic layer is

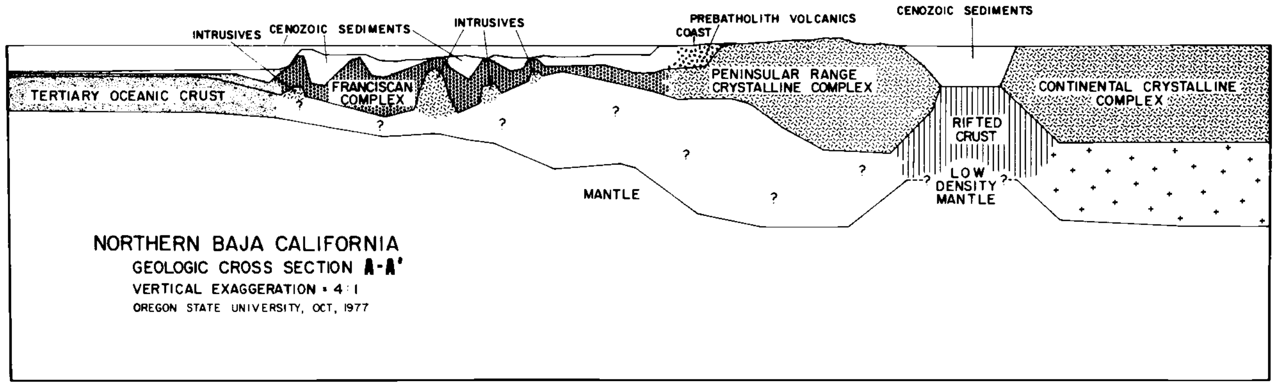


Figure 12. Geologic interpretation of crustal and subcrustal section A-A'.

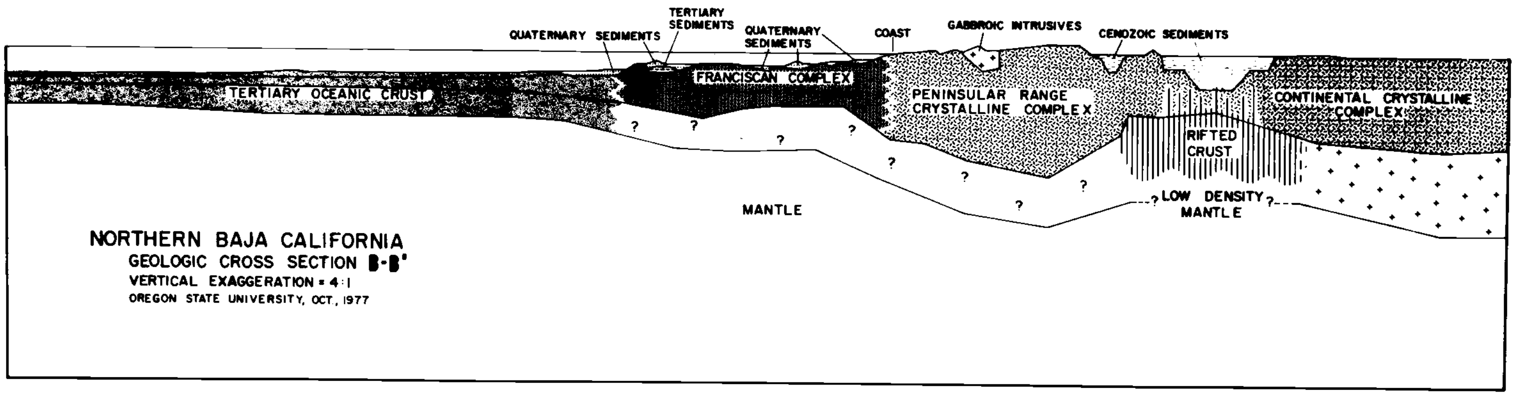


Figure 13. Geologic interpretation of crustal and subcrustal section B-B'.

included in the rocks interpreted as Franciscan basement. Serpentinite has magnetizations and densities similar to those used in the geophysical models (Cady, 1975) and is known to occur in the Borderland (Vedder _et al._, 1974). In northern California, Bailey _et al._ (1970) interpret the major serpentinite units to be an ophiolite complex, structurally above the Franciscan, with the lower Great Valley Sequence in depositional contact upon the ophiolite. If a similar situation is the case in the Continental Borderland, then some of the rocks included in the Franciscan block on Figures 12 and 13 are probably analogous to the Great Valley Sequence.

The gravity data indicate the presence of high density rocks beneath several of the banks on section A-A'. As noted above, volcanic rocks have been dredged from many places in the Borderland. The rocks range from basalt to rhyodacite, with andesite the most common type, and are chiefly middle Miocene in age (Vedder _et al._, 1974). This suggests that the high density rocks may be the intrusive sources for the volcanics. An alternate interpretation would be that the high density rocks are fault blocks of mafic or ultramafic rocks which were originally part of the lower crust or upper mantle. It is likely that both faulting and intrusion are responsible for some of the gravity highs.

No similar intrusions (or fault blocks) are shown on section B-B'. Figure 4 shows that the area crossed by B-B' does not have the large positive gravity anomalies found on A-A'. However, large gravity anomalies are found farther south, such as over Soledad Ridge, where Doyle and Gorsline (1977) report very recent basaltic rocks. This suggests the presence of intrusive rock masses similar to those postulated under section A-A'.

The lower crustal layer of 2.9 gr/cc is shown with question marks on part of Figures 12 and 13. The nature of these rocks depends on the process of subducting a spreading ridge. If spreading and associated igneous activity stopped when the ridge was subducted and then started again when the Gulf of California and Imperial Valley began to open, then the lower crustal layer may be simply old oceanic crust subducted beneath the continent before the ridge reached the trench. If, on the other hand, the spreading and intrusion continued as the former ridge was overridden by the continent then the lower crustal rocks may be some mixture of rocks from the old acretionary prism and the continent which have been deformed, metamorphosed and intruded. The average age of volcanic rocks from the Borderland is 15.2 million years (Yeats and Turner, 1969) and agrees closely with the time of ridge subduction as determined by magnetic anomalies. This would tend to favor the second hypothesis.

As noted above, section A-A' indicates that this lower crustal layer thickens and extends to within less than 4 km of the surface 50 km west of the Coronado Escarpment. The depth to mantle and thickness of the high density lower crust are quite similar to the Imperial Valley and Colorado Delta area. The possibility exists that this area was an active site of crustal rifting after subduction of the ridge but prior to initiation of spreading and transform faulting in the Imperial Valley and Gulf of California.

The seismic refraction profiles of Shor and Raitt (1958) show that the mantle is about 17.5 km deep under the Patton Escarpment and 24 km deep under the San Diego Trough. Section A-A' is farther south than B-B' and indicates a mantle depth of about 12 to 13 km under the Patton Escarpment and 17.5 km farther east. Section B-B' is even farther south and shows mantle depths of about 13 to 14 km at the outer escarpment and 15 km near the coast. Therefore, there seems to be a systematic decrease in mantle depth under the Borderland from north to south.

Doyle and Gorsline (1977) argue that the whole Borderland is an east-west trending synclinorium formed by north-south compression. Their theory is based primarily on a plot of the depths to ridge tops and basins against latitude. This plot (Doyle and Gorsline, 1977, Figure 4) shows that depths increase southward to about 30°N Lat. and then decrease farther south. The evidence noted above for a decrease in mantle depths to the south does not support the idea of north-south compression. It is difficult to imagine how north-south compression could cause the seafloor to drop and the mantle to rise.

Furthermore, the data of Doyle and Gorsline are subject to an alternative interpretation. It is quite possible to fit the ridge tops of their Figure 4 with a series of shorter, sub-horizontal segments, rather than the smooth curve they have used. These segments are: 32.75° to 32°N Lat., 32° to 31.2° N Lat., and 31.2° to 29° N Lat. When interpreted in this way the data suggest block faulting and north-south extension. This is more consistent with the shallower mantle which could easily result from thinning of the crust due to extension.

Sections A-A' and B-B' show somewhat different structures in the Imperial Valley and Colorado Delta. On B-B' rocks of 2.67 gr/cc are modeled all the way across this structure. On A-A' however, sediments rest directly on high density material. In Figures 12 and 13 the 2.67 gr/cc layer is interpreted as part of the Peninsular Ranges and Continental Crystalline Complexes. The cross sections therefore suggest that the crust is completely rifted on A-A' but only thinned on B-B'.

This interpretation of the fine structure on the Imperial Valley may be in error. The overall trend of the Imperial Valley is reasonably two dimensional. However, present theories hold that the Imperial Valley is opening along a series of transform faults and offset spreading centers (Elders *et al.*, 1972). Sections A-A' and B-B' cross the hypothetical spreading centers at Brawley, California, and Cerro Prieto, Baja California respectively. However, the direction of spreading is perpendicular to the direction of the sections. This means that the detailed structure probably does not well satisfy the two dimensional assumption used in the models.

Figures 12 and 13 indicate that the width of the area being rifted is 40 km larger under B-B' than under A-A'. The zone of rifted lower crust seems to extend west at least as far as the Laguna Salada under B-B'. This is consistent with the geologic map of Gastil et al. (1975) which shows this area to be broken by numerous normal faults, which indicate extension of the crust.

The fact that the geophysical section is quite consistent with the available surficial geology implies that the differences in rift structures on the two sections are not entirely artifacts of the modeling technique. It may be that in the Brawley area the crust has been rifted completely along a relatively narrow zone. This may reflect differences in the upper mantle spreading centers, differences in the overlying crustal structure, or a combination of the two.

As noted previously, a low density upper mantle is not necessary to model the gravity anomalies in the Imperial Valley and Colorado Delta area. This does not mean that a low density zone does not exist in the upper mantle under this area, but only that it is not of sufficient size or density contrast to effect the gravity model. The high heat flow, crustal extension, and volcanism in the Imperial Valley suggests that the upper mantle is hotter than normal in this area. This in turn makes it quite likely that there is at least some density differences due to thermal expansion in the upper mantle. Therefore, the possibility of a low density upper mantle is noted in Figures 12 and 13 even though it is not required in the gravity models.

# CONCLUSIONS

Gravity, magnetic, seismic and geologic data indicate that the crustal structure under the Continental Borderland is transitional between oceanic crust to the west and continental crust to the east. The data indicate that the mantle is at a depth of 9.7 km under the oceanic crust west of the area. Under the Outer Ridge the mantle is about 12 km deep. East of this the top of the mantle deepens irregularly to a maximum of 27 km under the Peninsular Ranges.

When compared with the seismic refraction line of Shor and Raitt (1958) the computed cross sections indicate that the mantle under the Borderland rises from north to south. This does not support the hypothesis of Doyle and Gorsline (1977) that the Borderland is a broad synclinorium resulting from north-south compression. Instead the mantle depths are more consistent with north-south extension of the Borderland. The principal evidence on which Doyle and Gorsline base their hypothesis can be reinterpreted to support north-south extension.

Mantle depths of about 20 km are indicated under the Imperial Valley and Colorado Delta. This is consistent with depths determined by previous workers (Phillips, 1964; Gibbs and Roller, 1966; Elders et al., 1972). A low density upper mantle, if present in this region is not detectable by the methods used in this study. The data suggest that the crust is completely rifted under the Brawley geothermal anomaly. Farther south, in the vicinity of Laguna Salada and Cerro Prieto the crust is thinned over a wider zone but may not be completedly rifted.

The age of the youngest detectable remnant magnetic anomaly at the edge of the Borderland decreases to the south. A magnetic anomaly associated with a northward continuation of the San Benito Fault Zone is not detected by this study. A buried trench-like depression is present at the base of the Outer Ridge (31.3°N Lat, 119.3°W Long.) and is filled with about 2 km of sediments. Gravity data indicate that this feature extends along the base of the Patton Escarpment to north of 33°N Lat.

The geophysical data is interpreted as indicating a structural section of Franciscan rocks about 6 km thick which extends from the west edge of the Borderland to the Coronado Escarpment. The nature of the contacts between the Franciscan and the oceanic crust to the west and Continental crust to east is not indicated by the data used in this study. Magnetic data suggest that an ophiolite may be present within or on top of the Franciscan rocks.

Several of the ridges in the Borderland have a core of high density rocks which are probably intrusives. These intrusive masses are most common in the area north of the Santo Tomas Fault. The general structure of the Borderland is more complicated on the north side of this fault. The area just south of the San Clemente Basin and the San Diego Trough has an anomalously thin upper crust. The gross structure of this region is comparable to the Imperial Valley and may represent a former site of rifting related to subduction of the East Pacific Rise.

North of the Santo Tomas Fault are several basins with sediment fills in excess of 3 km. South of the Santo Tomas Fault the sediment cover is discontinuous and generally less than 2 km thick.

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# APPENDIX

# APPENDIX

Computer listings of the following programs are contained in this appendix. These programs are used in reducing and analyzing marine gravity data.

NEWGRAV: (Gemperle, M., OSU) Changes gravity anomaly values on an OSU gravity data file from those based on a Commerce Building Pier (Washington, D. C.) gravity value of 980.1188 gals and the 1930 International Gravity Formula to gravity anomaly values based on a Commerce Building Pier gravity value of 980.10430 gals and the 1967 International Gravity Formula (International Association of Geodesy, 1971; Morelli, 1971).

DEPITP: (Connard, G., OSU) Interpolates to fill any blanks in the bathymetry data which is included in an OSU gravity data file.

FAATOSBA: (Connard, G., OSU) Changes free-air gravity anomalies on an OSU gravity data file to simple Bouguer gravity anomalies. Sea water is replaced with a slab of density 2.67 gr/cc.

```
      PROGRAM FAATOSBA
C  CHANGES FREE AIR ANOM TO SIMPLE BOUGUER IN NGDCBIN FILE
      DIMENSION IND(15,100),IHDR(20)
      READ(1,105)IHDR
  105 FORMAT(20A4)
      IHDR(16)=4H SBA
      IHDR(17)=4H FOR
      IHDR(18)=4H FAA
      WRITE(61,103) (IHDR(I),I=1,18)
  103 FORMAT(1H ,18A4)
      BUFFER OUT(2,0) (IHDR,IHDR(20))
   30 BUFFER IN(1,1)(IND,IND(15,100))
      IF(EOF(1)) GO TO 60
      J=LENGTHF(1)/15
      DO 50 I=1,J
      IF(IND(14,I).EQ.100000) GO TO 50
      IF(IND(10,I).NE.100000) GO TO 48
      IND(14,I)=100000
      GO TO 50
   48 IND(14,I)=IND(14,I)+IFIX(.6886*FLOAT(IND(10,I)))
      IC=IC+1
   50 CONTINUE
      BUFFER OUT (2,1) (IND,IND(15,J))
      GO TO 30
   60 ENDFILE 2
      WRITE(61,106) IC
  106 FORMAT('0',I8,' RECORDS ALTERED')
      END
```

```
      PROGRAM NEWGRAV
C
C  VERSION 1   -  10/30/74  GEMPERLE
C  VERSION 1.1 - 2/26/75  ERROR CORRECTED GEMPERLE
C  PROGRAM CHANGES OLD GRAVITY ANOMALIES ON NGDCBIN TAPE
C  TO NEW ONES.  OTHER VARIABLES REMAIN THE SAME.
C  OLD ANOM. BASED ON:
C       COMM. PIER G = 980118.8
C       THEOG = 978049. * (1. + .0052884 * SIN(LAT)**2 -
C                    .0000059 * SIN(2*LAT)**2)
C  NEW ANOM BASED ON:
C       COMM. PIER G = 980104.30
C       THEOG = 978031.85 * (1. + .005278895 * SIN(LAT)**2 +
C                    .000023462 * SIN(LAT)**4)
C  (PROGRAM NGDCMG CHANGED OCT. 74 TO INCORPORATE NEW VALUES)
C  THEREFORE:
C       NEW ANOM = OLD ANOM + DELTA ANOM
C  WHERE
C       DELTA ANOM = 2.65+(-13.695+.135*SIN(LAT)**2)*SIN(LAT)**2
C
C    EQUIP,1=OLD NGDCBIN
C    EQUIP,2=NEW NGDCBIN
C    INPUT MAX. NO. OF FILE TO PROCESS ON LUN 60
C
C
      COMMON IDATA(15,100),HDR(10)
      DIMENSION IHDR(2)
      EQUIVALENCE (HDR(10),IHDR)
      R=3.141592653/180.
      CALL DATE(ADATE)
      CALL ARMYTIME(ATIME)
      CHDR=8HNEWGRAV2
      WRITE(61,100)
  100 FORMAT('0NEWGRAV - V1  10-30-74')
C  GET MAX NO OF FILES TO PROCESS
      WRITE(61,104)
  104 FORMAT('0GIVE MAX NO OF FILES TO PROCESS - I2')
      READ(60,105)KK
  105 FORMAT(I2)
      K=0
    5 BUFFER IN (1,0) (HDR,IHDR(2))
      IF(.NOT.EOF(1))GOTO10
    7 WRITE(61,106)K
  106 FORMAT('0',I4,' FILES PROCESSED')
      REWIND 2
      REWIND 1
      CALL EXIT
C  WRITE OLD AND NEW HEADER ON LUN 61, NEW HEADER ON LUN 2
   10 WRITE(61,102)HDR
      HDR(4)=ADATE
      HDR(5)=ATIME
      HDR(10)=CHDR
      WRITE(61,103)HDR
      BUFFER OUT (2,0) (HDR,IHDR(2))
  102 FORMAT('0',10A8)
  103 FORMAT(' ',10A8)
      K=K+1
C  GET SOME DATA
   20 BUFFER IN (1,1) (IDATA,IDATA(15,100))
      IF(.NOT.EOF(1))GOTO30
      ENDFILE 2
      IF(K.GE.KK)GOTO7
      GOTO5
   30 I=0
      L=LENGTHF(1)/15
   40 I=I+1
```

```
C   IF GRAV ANOM PRESENT, COMPUTE NEW ANOM
      IF(IDATA(14,I).EQ.100000)GOTO50
      TEMP=IDATA(4,I)*R/10000.
      TEMP=SIN(TEMP)**2
      DELTA=2.65+(-13.695+.135*TEMP)*TEMP
      IDELTA=DELTA*10. + SIGNF(.5,DELTA)
      IDATA(14,I)=IDATA(14,I)+IDELTA
   50 IF(I.LT.L)GOTO40
      BUFFER OUT (2,1) (IDATA,IDATA(15,L))
      GOTO20
      END
```

```
      PROGRAM DEPITP
C  VER 1    3/31/77   CONNARD
C     INTERPOLATES CORRECTED METERS VALUES TO FILL ANY
C  BLANKS IN NGDCBIN FILE. THIS IS NECESSARY TO COMPUTE
C  GRAVITY ANOMALIES
      DIMENSION ID(15,100,2),HDR(10),L(2)
      CHDR=8HITP. MET
      MET=10
      MATHEW=11
      WRITE(61,100)
  100 FORMAT('0DEPITP - V1  3/31/77')
      BUFFER IN (1,0) (HDR,HDR(10))
      IF(.NOT.EOF(1)) GO TO 2
      WRITE(61,101)
  101 FORMAT(' DATA FILE IS EMPTY')
      CALL EXIT
    2 WRITE(61,102)HDR
  102 FORMAT('0',10A8)
      HDR(8)=CHDR
      WRITE(61,102)HDR
      BUFFER OUT(2,0)(HDR,HDR(80))
      IDIS1=0
      IDIS3=0
      L(1)=0
      L(2)=0
      LL=0
      GO TO 40
C  NORMAL PROCESSING
    5 I=I+1
      IF(I.GT.L(LL)) GO TO 40
      IF(ID(MET,I,LL).EQ.100000) GO TO 10
      IF(ITP.NE.0) GO TO 20
      IDIS1=ID(15,I,LL)
      MET1=ID(MET,I,LL)
      GO TO 5
   10 IF(ITP.NE.0) GO TO 5
      I1=I
      ITP=1
      GO TO 5
C  GOT 2ND DEPTH NOW START INTERPOLATING
   20 I2=I-1
      IDIS3=ID(15,I,LL)
      MET3=ID(MET,I,LL)
      DO 30 J=I1,I2
      ID(MATHEW,J,LL)=99
      TEMP=FLOAT((MET3-MET1)*(ID(15,J,LL)-IDIS1))/
     1     FLOAT(IDIS3-IDIS1)
   30 ID(MET,J,LL)=IFIX(TEMP+SIGN(.5,TEMP))+MET1
      IDIS1=IDIS3
      MET1=MET3
      ITP=0
      GO TO 5
```

```
C     END OF BLOCK ROUTINE
      40 I=0
         LO=LL
         LENO=L(LO)
         LL=LL+1
         IF(LL.EQ.3) LL=1
         BUFFER IN(1,1)(ID(1,1,LL),ID(15,100,LL))
         IF(EOF(1)) GO TO 90
         L(LL)=LENGTHF(1)/15
         IF(LO.EQ.0) GO TO 50
         IF(ITP.EQ.0) GO TO 67
         I2=L(LO)
      60 I=I+1
         IF(ID(MET,I,LL).EQ.10000) GO TO 60
         IDIS3=ID(15,I,LL)
         MET3=ID(MET,I,LL)
         IF(IDIS3-IDIS1.GT.500) GO TO 67
         DO 65 J=I1,I2
         ID(MATHEW,J,LO)=99
         TEMP=FLOAT((MET3-MET1)*(ID(15,J,LO)-IDIS1))/
        1     FLOAT(IDIS3-IDIS1)
      65 ID(MET,J,LO)=IFIX(TEMP+SIGN(.5,TEMP)) +MET1
C     FINISHED WITH OLD BLOCK
      67 BUFFER OUT (2,1) (ID(1,1,LO),ID(15,LENO,LO))
         IF(ID(15,1,LL)-IDIS1.GT.500) GO TO 50
         I=0
         GO TO 5
C     HERE AT START OF RUN OR BREAK IN DATA
      50 I=0
      51 IF(ID(MET,I+1,LL).NE.100000) GO TO 5
         I=I+1
         GO TO 51
C     HERE  ON EOF
      90 BUFFER OUT (2,1) (ID(1,1,LO),ID(15,LENO,LO))
         ENDFILE 2
         END
```