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Title: GEOLOGIC STRUCTURE OF THE WESTERN CONTINENTAL MARGIN OF SOUTH CENTRAL BAJA CALIFORNIA BASED ON SEISMIC AND POTENTIAL FIELD DATA

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Marine geophysical data from the continental margin of Baja California and the Gulf of California, and geological and geophysical data from the Baja California Peninsula and mainland Mexico, outline the major geologic and tectonic features of the Baja California Peninsula and the surrounding areas from 24.5^{o} N. Lat. to 27.5^{o} N. Lat. A crustal and subcrustal cross section consistent with observed gravity and magnetic anomalies, and constrained by seismic refraction stations and the mapped surface geology shows major variations of density and magnetization in these areas. A geologic interpretation of the cross section indicates the rocks of the Pacific continental margin are composed of unconsolidated and semiconsolidated sediments, Tertiary sedimentary rock, metamorphic rock of Franciscan type, and continental crystalline rock probably corresponding to the Peninsular Range batholith. The depth to mantle under the Baja California

Peninsula is postulated to be 20 km. In the Gulf of California a section of low-density mantle beginning at a depth of 11 km is necessary to fit the observed gravity values and accounts for the low seismic velocities associated with the mantle in the Gulf. The correlation between the observed magnetic anomalies on the Pacific continental margin of the Baja California Peninsula and the theoretical magnetic anomalies expected from a spreading center shows that the youngest identifiable remanent anomaly on the Pacific side of south central Baja California is anomaly 3' formed at 6 my B.P. The remanent magnetic anomalies extend 50 km landward from the western edge of the continental slope.

Geologic Structure of the Western Continental Margin of South Central Baja California Based on Seismic and Potential Field Data

by

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INTRODUCTION

The 1300 km long Baja California Peninsula is a highly interesting and unique area from the standpoint of plate tectonics. Previous work by Hamilton (1961), Rusnak and Fisher (1964), Moore and Buffington (1968), and Atwater (1970) has established that the separation of Baja California from mainland Mexico is accomplished along strike-slip transform faults associated with spreading on the East Pacific Rise in the Gulf of California. However, the nature of the interaction between the East Pacific Rise and the North American continent has not been fully determined and little work has been done on the Pacific side of the south central Baja California Peninsula to determine the geologic structure of the continental margin.

During July and August, 1975, and July, 1976, personnel of the Direccion General de Oceanografica, Secretaria de Marina, Mexico, and the School of Oceanography, Oregon State University, aboard the Mexican Navy ship *Dragaminas Veinte*, conducted a joint geophysical investigation of the continental margin of the Baja California Peninsula and the Gulf of California. These cruises, Baja-75 and Baja-76, collected gravity and magnetic data along 17,000 km of trackline and also collected seismic reflection and wide angle reflection (WAR) data at selected locations. The author participated in the Baja-76 cruise.

This study uses the data obtained from the two Baja cruises, previous cruises of the Oregon State University School of Oceanography, and previously published data to investigate the crustal and subcrustal structure of the continental margin of Baja California, Peninsular Baja, the Gulf of California, and mainland Mexico from 24.5° N. Lat. to 27.5° N. Lat. This work is the first comprehensive structural investigation of the continental margin of the Baja California Peninsula in this area. An interpretation of the geophysical data yields a crustal and subcrustal cross section of the structure in the area from the abyssal seafloor across the Baja California Peninsula and into mainland Mexico. A free-air gravity anomaly map and a total field magnetic anomaly map show lateral variations in structure. The correlation of observed magnetic anomalies with the theoretical magnetic anomalies expected over a spreading center gives an indication of the time sequence of events associated with the overriding of the East Pacific Rise by the North American continent.

GEOLOGY OF SOUTHERN BAJA CALIFORNIA

The Baja California Peninsula forms a part of the North American Cordillera. The Peninsula is 1300 km in length with the width varying between 48 km and 240 km. Figure 1 shows a geologic map of the southern part of the Peninsula generalized after a map prepared by Lopez Ramos (1976).

Paleozoic rocks do not outcrop in the area from 24.5° N. Lat. to 27.5° N. Lat. and are rare on the rest of the Peninsula. Mesozoic intrusive rocks associated with the Peninsular Range batholith do not outcrop from 24.5° N. Lat. to 27.5° N. Lat. but outcrop extensively north of 28° N. Lat. and at the southern tip of the Peninsula, forming the Cape Massif. At the southern tip of the Peninsula the batholith outcrops in the upraised areas of a graben and horst structure confirming it lies underneath the surface rock. Krummenacher and Gastil (1970) report K/Ar dates from Mesozoic intrusive rocks in the northern part of the Peninsula ranging from 62.6 my B.P. to 107.5 my B.P. They also report dates from Mesozoic intrusive rocks at the southern tip of the Peninsula ranging from 62.6 my B.P. to 66.8 my B.P. Yeats (written communication, 1977) reports ages of 75 my B.P. and 85 my B.P. from K/Ar dating of two samples from Cabo San Lucas at the southern tip of the Peninsula. The batholith ranges in composition from quartz gabbro to granite

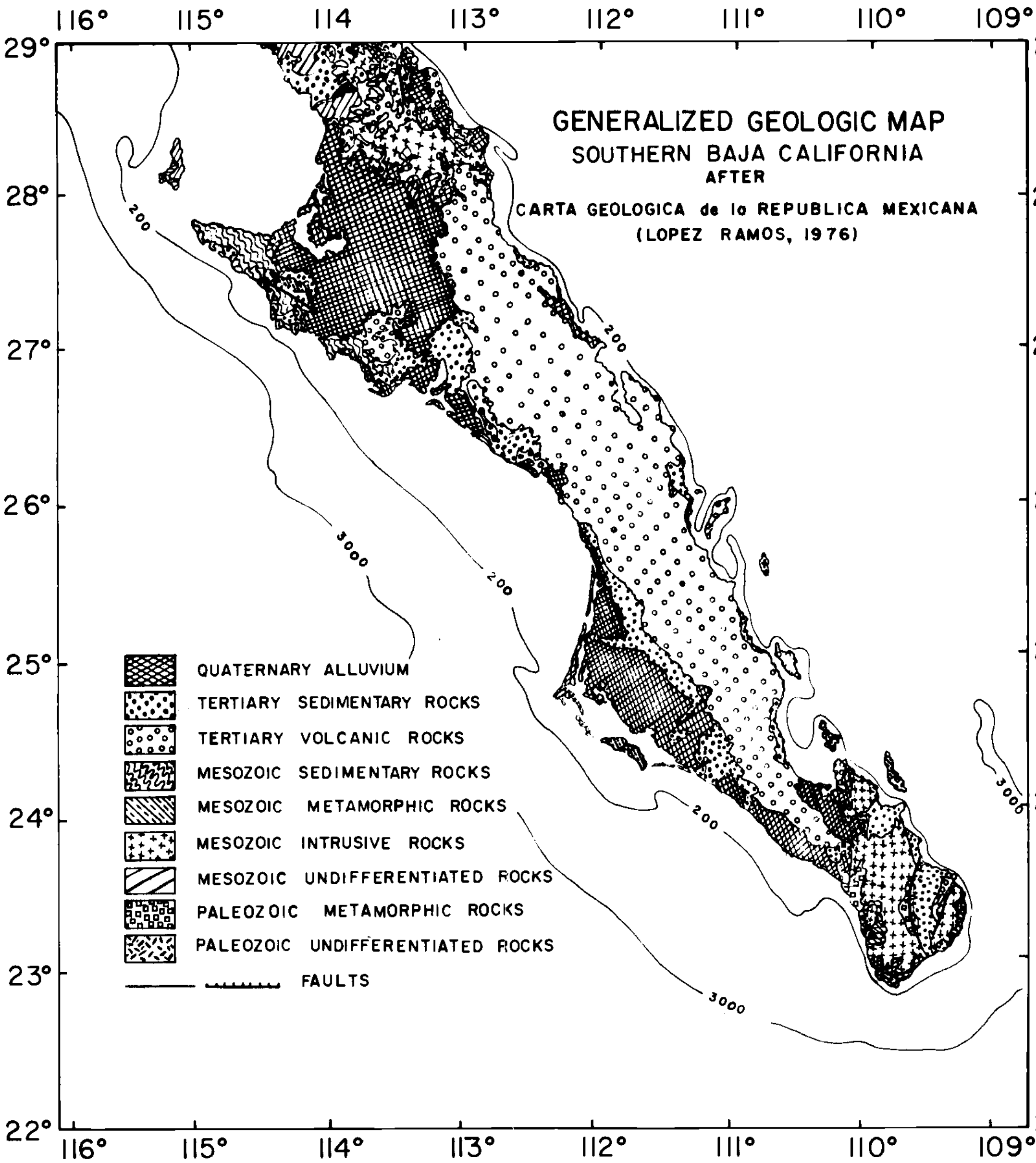

Figure 1. Geologic and tectonic map of southern Baja California (after Lopez Ramos, 1976).

with the dominant rock types being quartz diorite, tonalite, and granodiorite (Beal, 1948; Gastil, 1975).

Mesozoic metamorphic rocks outcrop on the Sebastian Vizcaino Peninsula at 27.4^{o}N. Lat., 114.3^{o} W. Long. and also around Magdalena Bay at 24.5^{o} N. Lat., 111.8^{o} W. Long. Yeats (written communication, 1977) states that the rocks on Santa Margarita Island at 24.5^{o} N. Lat., 111.9^{o} W. Long. consist of red and grey metachert, argillite, metagreywacke, chlorite schist, and schistose greenstone intercalated with serpentine, amphibolite, hornblende gneiss and garnet hornblende rock. He also states that the basement rocks of Santa Margarita Island and the neighboring Magdalena Island are similar to parts of the Franciscan Formation of California in lithology, type of metamorphism, and age of metamorphism. Jones et al. (1976) describe an outcrop of Mesozoic metamorphic rock on the Sebastian Vizcaino Peninsula as belonging to a Franciscan "belt" and state that the outcrop contains blueschist, metabasalt, metachert, and serpentine.

Mesozoic sedimentary rocks with some metasediments form a large part of the Sebastian Vizcaino Peninsula near 27.5^{o} N. Lat., 114.5^{o} W. Long. Jones et al. (1976) refer to these rocks as being similar to the Western Foothills belt of central California and map the rocks as slate and greywacke. Mina (1957) states that the Mesozoic sedimentary rocks on the Sebastian Vizcaino Peninsula contain shale, sandstone, and conglomerate.

Tertiary volcanic rocks largely of the Comondu Formation outcrop extensively in the area. This formation is composed of andesitic volcanic, pyroclastic, and related epiclastic rocks (Allison, 1964). Gastil et al. (1974) give ages for the Comondu Formation ranging from 22 my B.P. to 8 my B.P. with the younger ages associated with the clastic rocks derived from the volcanics.

Tertiary sedimentary rock outcrops are not prominent in the study area. The ages of the Tertiary sedimentary rocks range from Eocene to Pliocene with the greatest number of formations being deposited in Miocene time. The Tertiary sedimentary formations generally consist of shale, sandstones, and conglomerates deposited in a marine and coastal environment (Mina, 1957). Quaternary alluvium covers a large portion of the Sebastian Vizcaino Peninsula at 27.5^{o} N. Lat., 113.5^{o} W. Long. and Cabo San Lazaro at 24.7^{o} N. Lat., 111.7^{o} W. Long.

The interaction between the East Pacific Rise and the North American continent has formed the tectonic framework of the Baja California Peninsula. The East Pacific Rise curves to the east southwest of the Peninsula and enters the Gulf of California by a series of transform faults. This pattern continues through the Gulf as a series of transform faults offsetting small segments of the Rise. There are no transpeninsular faults mapped in the area from 24.5° N. Lat. to 27.5° N. Lat. The only faults visible in the area are minor normal faults on the Sebastian Vizcaino Peninsula.

PREVIOUS THEORIES ON THE GENESIS OF THE BAJA CALIFORNIA PENINSULA

Several theories have been proposed to explain the formation of the Gulf of California and the Baja California Peninsula. The earlier pre-plate tectonics theories are largely just of historical interest. Wegener (1924) suggested that the Gulf was opened by a thrust of the continental landmass to the south-southeast with the Baja California Peninsula remaining behind because of oceanic crustal resistance at the southern tip of the Peninsula. As evidence for this theory he observed that the tip of the Peninsula is thickened like an anvil presumably because of this resistance and that the Peninsula appears foreshortened when compared to the distance from Cabo Corrientes on mainland Mexico to the northern boundary of the Gulf. This section from Cabo Corrientes on mainland Mexico to the northern boundary of the Gulf is the part of the Mexican mainland from which Wegener thought the Peninsula separated. Beal (1948) favored the hypothesis that the Peninsula was elevated by compressive forces acting normal to it. Wisser (1954) thought the Gulf was formed by a zone of great faults along the western edge of a Pliocene uplift. The crestal portion of this uplift dropped as a half-graben along these faults opening the Gulf. Carey (1958) considered the Gulf of California to be a rhombochasm, a parallel-sided gap in the sialic crustal material which is occupied by simatic crustal material. Durham and Allison (1960) stated that the Baja California Peninsula and the Gulf of California were probably recognizable after the mid-Cretaceous orogeny associated with the emplacement of the Peninsular Range batholith though they do not provide a mechanism. These ancestral landforms have been modified by later tectonic events to produce the current structure of the area. Hamilton (1961) suggested that Baja California may have formed by the thinning, rupturing, and drifting of a piece of the Mexican mainland with heavier mantle material flowing into the gap behind the moving plate thereby forming the present Gulf floor. He also thought that strike-slip faulting in the Gulf and on the San Andreas Fault system in California is caused by flow currents in deeper materials. Rusnak and Fisher (1964) suggested that the Gulf of California evolved as fractured plates of crustal material moved northwest-ward and Pacific-ward by gravitational sliding on slopes caused by the uplifting of western Mexico by batholithic intrusions. Wilson (1965) believed the Gulf evolved from movement on a single ridge-ridge transform fault extending from the East Pacific Rise at the mouth of the Gulf to the Gorda Ridge and Juan de Fuca Ridge north of Cape Mendocino. Vine (1966) agreed with the mechanism proposed by Wilson but pictured a series of en echelon transform faults in the Gulf.

Atwater (1970) and Atwater and Molnar (1973) presented models for the interaction between the East Pacific Rise and the North

American continent using the remanent magnetic lineations in the northeastern Pacific oceanic crust as a guide. In the northeast Pacific the crust containing the eastern half of the remanent magnetic anomalies expected over a spreading center and the East Pacific Rise itself is not observed between north central Mexico and northern California. This missing crust, called the Farallon Plate (McKenzie and Morgan, 1969), and the associated East Pacific Rise, has been completely subducted along western North America. The age of the youngest magnetic anomalies along the continental margin gives a time when the East Pacific Rise was still active in the area. All the models presented by Atwater (1970) and Atwater and Molnar (1973) are variations on a main hypothesis that when the North American continent overrode the East Pacific Rise two triple junctions resulted. The northern triple junction was composed of a transform fault between the North American and Pacific plates, a transform fault offsetting the East Pacific Rise, and the trench between the Farallon plate and the North American continent. The southern triple junction was composed of the East Pacific Rise, the trench between the Farallon plate and the North American plate, and a transform fault between the Pacific plate and the North American continent. All the models presented propose 11 my B.P. as the time that subduction ceased along the Pacific continental margin of south central Baja California. Atwater (1970) states that from 11 my B.P. to 5 my B.P., the postulated time of opening of the Gulf of California, the boundary between the Pacific and North American plates was still hot and easily ruptured. Motion between the Pacific and North American plates, caused by spreading on the East Pacific Rise, was taken up by deformation of this boundary and also perhaps by deformation in the continental interior. Eventually the juncture between the two plates cooled and strengthened and the motion between the plates moved inland accelerating the motion of the San Andreas Fault system in the Gulf. This caused or increased the separation of the Baja California Peninsula from mainland Mexico.

PREVIOUS GEOPHYSICAL WORK PERTAINING TO THE AREA OR THE CRUSTAL CROSS SECTION

Bathymetry

Rusnak and Fisher (1964) analyzed the bathymetry collected in the Gulf of California by the Scripps Institute of Oceanography between 1957 and 1963. They interpreted the results to show indications of right-lateral movement with resulting tensional fractures, several northeast trending deeps, and *en echelon* faults oriented oblique to the trend of the Gulf. They also state that two main types of elevations occur in the Gulf, one associated with islands and banks along the western margin consisting largely of granite, and the other associated with highs in the central part of the Gulf containing basic volcanics. Krause (1965) conducted an intensive bathymetric survey of the Pacific continental margin of the Baja California Peninsula from 28.0° N. Lat. to 32.5° N. Lat. He found several southeast-northwest trending faults within the area and stated that the structure of the area results from a combination of many processes including right-lateral faulting between the oceanic basin and the continent. Larson (1972) used bathymetric profiles at the mouth of the Gulf to determine the form of the East Pacific Rise, the Tamayo Fracture Zone, and the Rivera Fracture Zone. He found that the East Pacific Rise is located to the west of the center of the Gulf and is truncated inside the Gulf by a series of northwest-trending fault scarps.

Gravity

Vening Meinesz (1948) published the first gravity readings obtained in the area of the Baja California continental margin from 24.5° N. Lat. to 27.5° N. Lat. He obtained three readings in the area and interpreted the readings to indicate overriding of the sea-floor by the continent. This was quite a remarkable interpretation for the pre-plate tectonic period. Worzel (1965) lists six submarine pendulum measurements obtained on the western continental margin of Baja California in the area of this report by the USS Chopper. Onshore gravity values for the Baja California Peninsula and mainland Mexico were obtained from the Department of Defense Gravity Library as were additional sea gravity readings both on the western continental margin of the Peninsula and in the Gulf of California. Cruises of the Oregon State University R/V Yaquina during 1969, 1971, and 1973, and a cruise by the Oregon State University R/V Wecoma during 1975 collected gravity data on the western continental margin of the Peninsula. Personnel from the School of Oceanography, Oregon State University, collected gravity and magnetic data on the western continental margin of the Peninsula and in the Gulf of California during a cruise from 6 July, 1975, to 6 August, 1975, on board the Mexican Navy ship Dragaminas Veinte. Figure 2 shows tracklines of these cruises, the Baja-76 cruise discussed in the

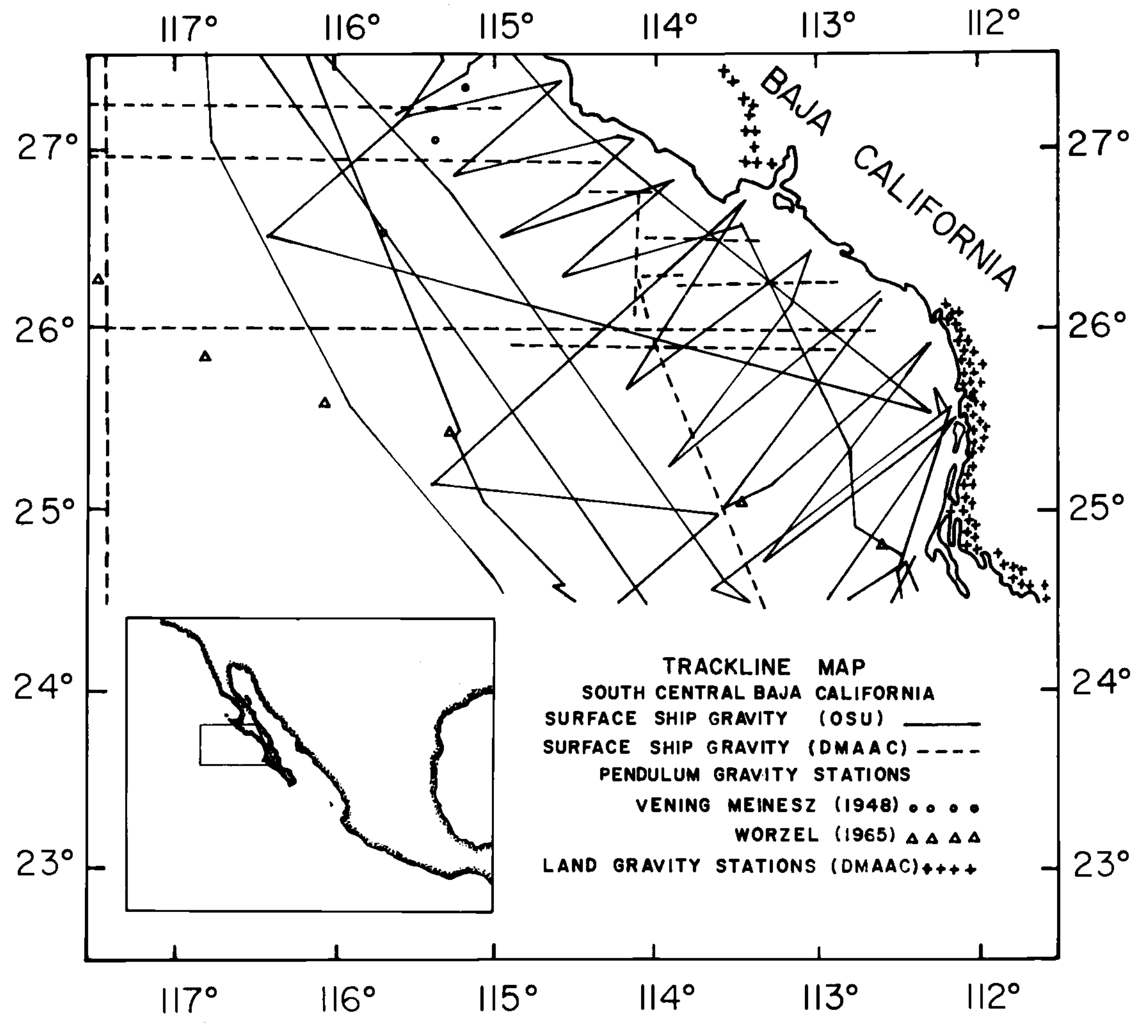

Figure 2. Location of geophysical measurements on the western coast and western continental margin of south central Baja California (OSU, DMAAC, Vening Meinesz (1948), Worzel (1965)). Gravity and magnetic data were obtained along the OSU surface ship tracklines. Other measurements are of gravity only.

section on New Data, and the data obtained from other sources used for the determination of the structure of the Pacific continental margin.

Harrison and Mathur (1964) obtained gravity readings in the Gulf of California on board the R/V Horizon. Their measurements show that the Gulf, approximately as far north as Guaymas at 28° N. Lat. is underlain by denser rocks than is the area surrounding the Gulf.

Magnetics

Hilde (1964) analyzed the results of a geomagnetic survey of the southern Gulf of California conducted by the Scripps Institute of Oceanography during November, 1959. He found that the magnetic anomaly patterns obtained trend northwest-southeast, the same as the topographic features, and that the second crustal layer is the magnetic layer.

Three cruises by the USNS Charles H. Davis to the Gulf of California, reported by Moore and Buffington (1968), produced profiles in the Gulf. They suggested that the present configuration of the Gulf results from spreading of the sea floor by crustal growth on the East Pacific Rise at the mouth of the Gulf and on spreading centers offset by en echelon faults in the Gulf.

The Scripps Institute of Oceanography has obtained magnetic data west of the Baja California Peninsula as reported by Atwater

(1970) and Chase et al. (1970). The measurements were generally made in deep water with few readings inside the 100 fathom contour. The most unusual feature of the magnetic anomaly lineations is the bend of the northern end of the anomalies to the west starting at approximately anomaly 5C at 17 my B.P. This suggests interaction with the continental plate. Chase et al. (1970) state that the spreading half-rate was 1.6 cm/yr north of 25^{o} N. Lat. at the time of anomaly 5A (12 my B.P.) and that anomaly 5A is the latest identifiable anomaly in the continental margin of the peninsula from 24.5^{o} N. Lat. to 27.5^{o} N. Lat.

Larson et al. (1968) report that magnetic anomaly profiles at the mouth of the Gulf indicate that the current half-rate of spreading in the Gulf is 3.0 cm/yr. Larson et al. (1972) report the results of a magnetic anomaly survey in the four deep-water basins of the central and southern Gulf of California. The survey produced no obvious magnetic lineations as would be expected from sea floor spreading on an active ridge. Klitgord et al. (1974) report the same results from the northern part of the Gulf. They suggest that rapid sedimentation from the adjacent land masses may hinder cooling and restrict the formation of the remanent magnetic stripes. They also state that the magnetic anomalies observed are associated with inferred transform faults. Neither author considers the lack of correlatable anomalies to be evidence against spreading in the Gulf.

Seismics

Phillips (1964) reported the results from 24 seismic refraction stations in the Gulf of California and two stations on the Pacific continental margin of the Baja Peninsula. Station 13 of Phillips' report provides a constraint for the crustal and subcrustal cross section discussed later in this thesis, while Station 25 and Station 26, located on the Pacific continental margin of the Peninsula, provide an indication of the depth to mantle. Phillips provides two possible interpretations for Station 13, one based on a two-layer crust and one based on a three-layer crust. Because both the northern and southern parts of the Gulf display a three-layer crust, this interpretation was chosen as a representation of the structure in the Gulf. The three-layer interpretation yields a crustal column of 1.69 km of water, 1.32 km of material with a velocity of 2.0 km/sec, 1.69 km of 5.50 km/sec material, and 6.67 km of material with a velocity of 6.72 km/sec. The subcrustal material at a depth of 11.37 km has a velocity of 7.25 km/sec. The empirical curve of Ludwig, Nafe, and Drake (1971) provides a means of relating seismic velocity to rock density. These curves yield densities of 2.0 gm/cc for the 2.0 km/sec layer, 2.60 gm/cc for the 5.50 km/sec layer, 2.90 gm/cc for the 6.72 km/sec layer, and 3.10 gm/cc for the subcrustal layer. On the Pacific continental margin of southern Baja California, Phillips (1964) obtains a mantle depth of 19.5 km. This depth was used only as an approximate indication of the depth to mantle for the cross section discussed later in this thesis because it was obtained further south than the cross section and there is a wide angle reflection line, discussed below under New Data, nearer the cross section.

Shor et al. (1970) report the results of two seismic refraction lines west of the Baja California Peninsula. Their results are used to tie the crustal cross section discussed later at the seaward end. Station CH14 at 22° N. Lat., 116.1° W. Long, yields the following structure: 3.83 km of water with a velocity of 1.495 km/sec, 0.32 km of sediment with a velocity of 2.15 km/sec, 0.97 km of 5.38 km/sec material, and 5.31 km of 6.78 km/sec material. The velocity obtained from the mantle is 8.24 km/sec with a depth to mantle of 10.43 km. Station CH15 at 24.5° N. Lat, 116.6° W. Long. shows 3.78 km of water with a velocity of 1.496 km/sec, 0.19 km of sediment with a velocity of 2.15 km/sec, 1.15 km of material with a velocity of 4.75 km/sec, and 4.89 km of material with a velocity of 6.70 km/sec. The subcrustal material lies at a depth of 10.01 km and has a velocity of 8.34 km/sec. The Ludwig, Nafe, and Drake (1971) curve again provides the means of relating these velocities to densities. These two stations allow for the interpretation of a three-layer crust with densities of 2.00 gm/cc for the upper sedimentary layer, 2.60 gm/cc for the middle crustal layer, and 2.90 gm/cc for the lower crustal layer. The density of the mantle is taken as 3.30 gm/cc. It should be noted that the velocity and hence the density obtained for the mantle is higher for CH14 and CH15 than at Station 13 of Phillips' (1964) in the Gulf.

McConnell and McTaggart-Cowan (1963) list the results of a seismic refraction station in mainland Mexico at 24.0° N. Lat., 104.2° W. Long. This station provides a constraint for the eastern end of the cross section. This station, at an elevation of 2.20 km, gives the following structure: 0.8 km of 3.0 km/sec material, 3.4 km of 5.0 km/sec material, 16.2 km of 6.0 km/sec material, 15.2 km of 6.4 km/sec material, and 8.8 km of 7.6 km/sec material. The mantle shows a velocity of 8.4 km/sec.

Moore and Buffington (1968) obtained seismic refraction profiles in the Gulf and around the Tamayo Fracture Zone where the East Pacific Rise enters the Gulf. They interpreted the data as showing spreading centers offset by _en echelon_ transform faults in the Gulf. Bischoff and Henyey (1973) obtained continuous seismic profiling in the northern Gulf region. They conclude that the structure of the Gulf is dominated by transform faults separated by short spreading ridge segments. They also note that the major faults on the Peninsula, such as the Agua Blanca Fault at 31.8° N. Lat., do not continue into the Gulf. Moore (1973) interpreted seismic reflection data in the Gulf to chart fracture zones in the Gulf then used these fracture zones and the estimated spreading rate on the East Pacific Rise in the Gulf to reconstruct the form of a proto-Gulf. Normark (1977) reports the results of nine seismic lines located on the Pacific continental margin of the Peninsula from 23.5^{o} N. Lat. to 29.3^{o} N. Lat. He states that there is a pronounced pattern of northwest-trending banks and ridges especially between 24.5^{o} N. Lat. and 26.3^{o} N. Lat. and that these features appear to be fault-bounded on many of the profiles. He suggests that because the trend of these features is close to the proposed direction of Pacific-North American plate motion between 10 my B.P. and 4.5 my B.P., it seems probable they were formed as a result of slivering of the continental margin by strike-slip faulting during transform fault movement.

No microearthquake studies of the Pacific continental margin of the Peninsula have been reported. Thatcher and Brune (1971) studied an earthquake swarm in the northern part of the Gulf near a proposed spreading center and found that the earthquakes were characterized by shallow hypocentral depths and predominantly normal faulting. Teleseismic P-delays from this earthquake swarm suggested anomalously low upper mantle velocities. Reid et al. (1972) used sonobuoys to investigate microearthquakes in the Gulf. They interpreted the results to show that earthquake swarms are associated with spreading centers, while other individual events delineate transform faults. Molnar (1973) determined four fault plane solutions for earthquakes in the Gulf and interpreted the results to show right-lateral, strike-slip faulting on northwesterly trending planes. Reichle et al. (1976) used sonobuoys to study two transform fault aftershock sequences in the Gulf and suggested that the earthquake generating zone is very thin, perhaps 3 to 5 km. Reichle and Reid (1977) studied three earthquake swarms in the Gulf and suggested that some swarm events may occur in consolidated sediments.

Heat Flow

Von Herzen and Maxwell (1963) reported the result of a heat-flow measurement located at 29° N. Lat., 117.5° W. Long. near Guadalupe Island. A heat-flow value of 2.81×10^{-6} cal/cm^2 sec was obtained, a very high value for the Pacific oceanic area. Von Herzen (1968) also reported the results of ten heat-flow measurements on the western continental borderland of the Baja California Peninsula above 28° N. Lat. The results show an average of 2.07×10^{-6} cal/cm^2 sec, nearly twice that for the average deep-sea regions. Von Herzen (1963) obtained measurements in the Gulf and found the geothermal flux to be much greater than the world-wide mean. The mean of the measurements in the Gulf is 3.12×10^{-6} cal/cm^2 sec compared with an an oceanic mean value of 1.2×10^{-6} cal/cm^2 sec. This is consistent with active, near-surface spreading centers in the Gulf.

NEW DATA

Personnel from the School of Oceanography, Oregon State University, collected geophysical data aboard the Mexican Navy ship Draguminas Veinte during the period 3 July, 1976, to 28 July, 1976. Gravity, bathymetric, magnetic, seismic reflection, and seismic wide angle reflection data were obtained both on the Pacific continental margin of the Baja California Peninsula and in the Gulf of Mexico. The tracklines from the 1976 cruise (Baja-76) are included in the surface ship (OSU) tracklines in Figure 2. The information below also applies to the cruise from 6 July, 1975, to 6 August, 1975, mentioned in the section on Previous Geophysical Work.

A Geometrics Model G803 Marine/Airborne Proton Magnetometer measured the total magnetic field of the earth. The magnetometer was towed approximately 180 meters behind the ship to insure that the magnetic field of the ship did not interfere with the readings. The total magnetic field was recorded every 30 seconds on magnetic tape and also recorded graphically.

Twelve kilohertz echo soundings recorded on an EPC graphic recorder provided bathymetric data. OSU personnel hand-digitized the data at a five-minute interval and on high and low points. The uncorrected measurements, in fathoms, were later corrected, using the Matthew's Tables to take into account the change of sound velocity with depth in the water column, and then converted to meters.

A 40-cubic inch air gun operating at 1500 psi with an 8-second firing rate provided the energy source for the seismic reflection and wide angle reflection lines. An EPC graphic recorder operating on a 4-second sweep rate recorded the outgoing and returning signals which were detected by a hydrophone streamer. A sonobuoy provided signal detection during the wide angle reflection work. The sonobuoy was placed in the water and the ship traveled away from it with the air gun firing at the 8-second firing rate. The sonobuoy detected the direct, reflected, and refracted signals and transmitted the information back to the shipboard EPC graphic recorder. The hydrophone streamer collected reflection data from directly behind the ship while the wide angle reflection line was being shot. This information was recorded on magnetic tape and later played into the EPC graphic recorder to produce a visual display.

Lacoste and Romberg Air-Sea Gravity Meter S42 with a stabilized platform measured changes in gravity. This meter corrects for vertical and horizontal accelerations and for cross-coupling between these accelerations. It is necessary to tie the gravity readings obtained from the shipboard meter to the International Gravity Standardization Net because the shipboard meter measures only relative changes in gravity. Table 1 lists the base ties used in the Baja-76 cruise. The same information applies to the Baja-75 cruise except that the 1975 cruise did not include the Guaymas station (Huehn, 1977).

Table 1. Gravity base ties for the Baja-75 and Baja-76 cruises.

Location	Gravity (mgal)	Source	Designation
San Diego	979517.7	Worzel (1965)	699f
Ensenada	979446.64	International Gravity Bureau	12016C
Guaymas	979164.77	Universidad Nacional Autonoma de Mexico	23
La Paz	978907.94	"	28
Mazatlan	978838.84	"	34

All values are from the DMAAC Reference Publication No. 25 (DMAAC, 1974) except the San Diego station. The San Diego station has been changed from Worzel's original value because the station has been tied to station WA453 of Woollard and Rose (1963) and also because of changes in the International Gravity Standardization Net since the Worzel (1965) reading (Gemperle, personal communication, 1977). Lacoste and Romberg land meter G-126 was used to obtain gravity readings on land. The drift correction for the shipboard meter was -10.7 mgals for the Baja-76 cruise over a period of 30 days. Gravity readings were recorded graphically in analog form and digitally on a data acquisition magnetic tape.

Omega fixes, radar fixes, and dead reckoning provided navigation for the cruise. Personnel of the Mexican Navy took Omega fixes at half-hour intervals and radar fixes generally at major course changes and intermittently between course changes depending on the range to the nearest landmark and the need. A tachometer measured shaft speeds and the output from the main gyro of the ship indicated changes in direction. These parameters were recorded on a data acquisition tape along with the gravity readings and also were displayed visually. Personnel of the School of Oceanography compared gravity and bathymetric values at crossing points between the Baja-76 cruise and the data acquired previously. The navigation was then corrected to minimize the difference in the gravity and bathymetric readings at these crossings. Then the bathymetry, magnetics gravity, position, course, speed, and trackline distance were merged by computer to give an output of magnetic and gravity anomalies versus location. During the computer processing the Eotvos correction was applied to the gravity data. This correction is needed because the movement of the ship across the earth's surface causes changes in the centrifugal acceleration brought about by the earth's rotation.

DATA INTERPRETATION

Bathymetric Contour Map

Figure 3 shows a bathymetric map of the seafloor adjacent to the south central Baja California Peninsula with contours at a 200 fathom interval. The bathymetric structures from the coast to the start of the abyssal plain strike subparallel to the trend of the Peninsula. At approximately 26°N. Lat., near the middle of the area, the continental shelf extends seaward approximately 110 km from the coastline. The continental slope extends approximately 65 km from the slope-shelf break to the southward extension of the Cedros Trench. The deepest contour in the area is 2400 fathoms (4.4 km) in the axis of the Cedros Trench. Seaward of the Cedros Trench and its southern extension the abyssal seafloor shows many seamounts and an irregular topography.

Bathymetry Projected on Tracklines

Figure 4 gives a perspective view of the bathymetry on selected tracklines through the area. The trackline denoted BB' coincides with the crustal and subcrustal cross section discussed later in this thesis. The numbers on the trackline BB' correspond to the distance in kilometers along the cross section. The continental shelf-continental slope break is fairly well determined through the area as

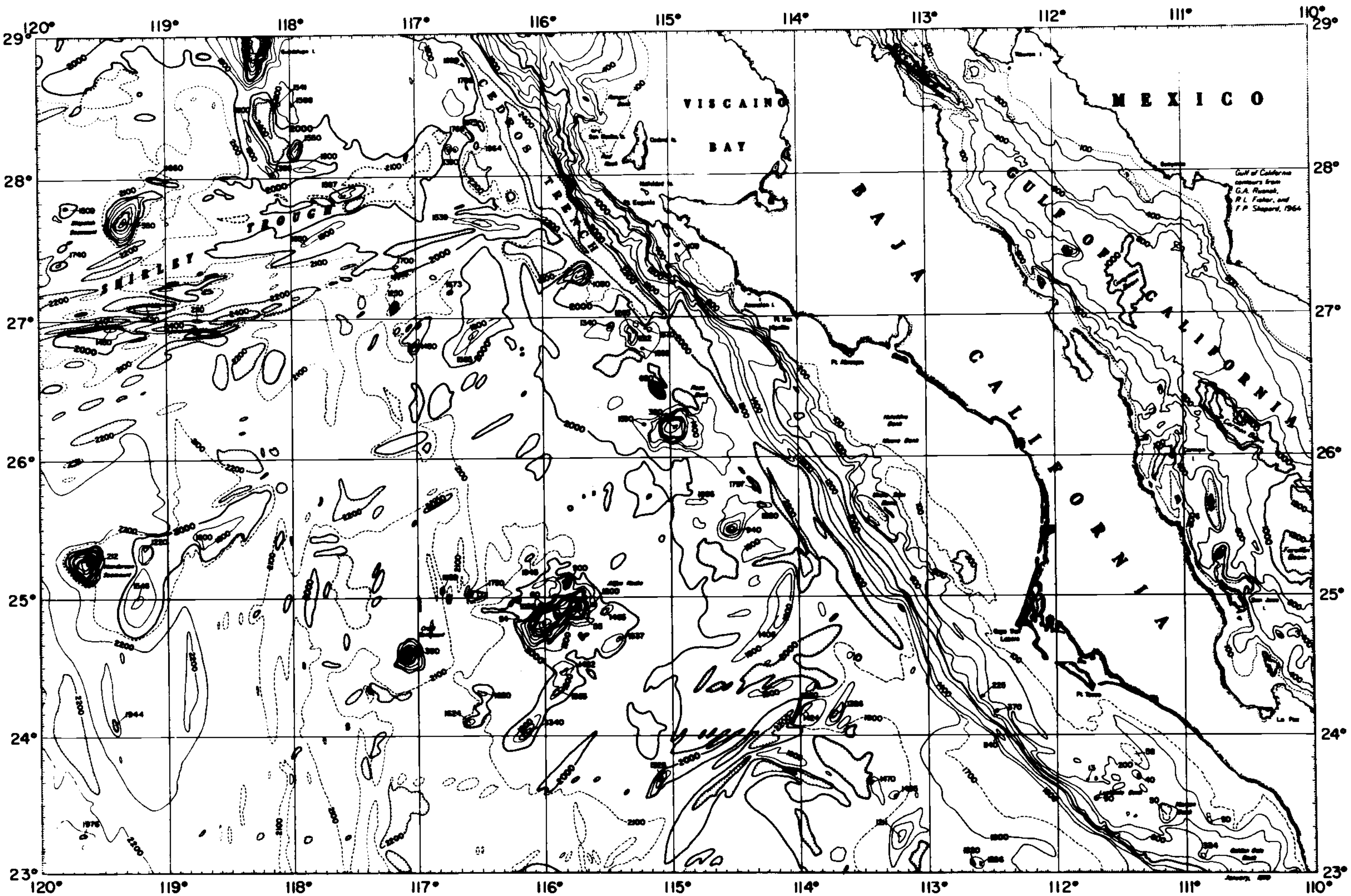

Figure 3. Bathymetric map of the seafloor adjacent to the Baja California Peninsula (USNOO, 1971).

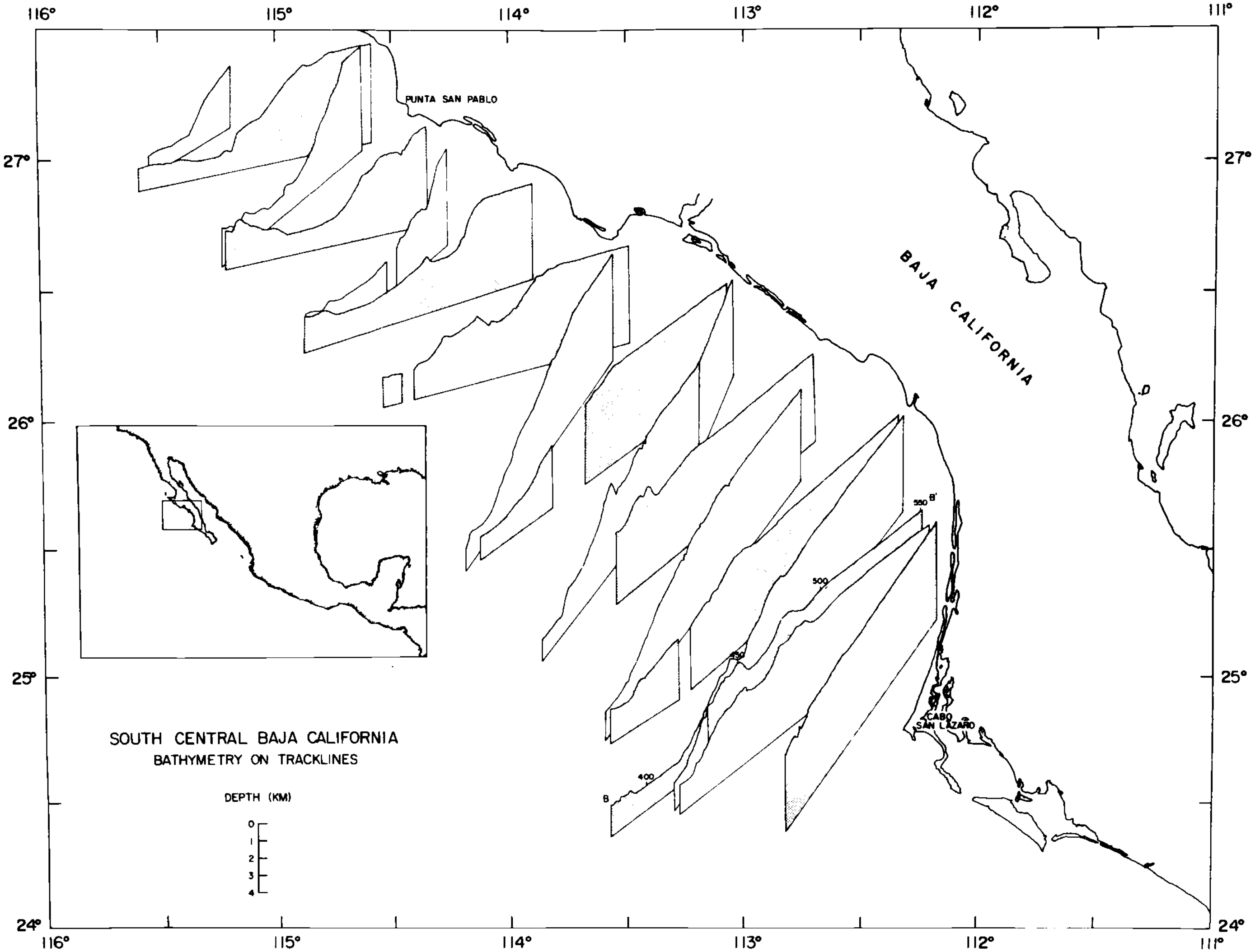

Figure 4. Perspective view of the bathymetry along selected tracklines across the continental margin of south central Baja California.

is the break between the continental slope and the southward extension of the Cedros Trench. The southern extension of the Cedros Trench appears as an essentially flat-floored deep visible at the seaward end of many of the profiles. The pronounced bathymetric high at 480 km trends north-northwest across six tracklines. This bathymetric high appears continuous with the outcrops of Mesozoic metamorphic rock observed on Magdalena Island and Santa Margarita Island, the islands south of Cabo San Lazaro. The bathymetric high at 450 km trends approximately north-south and is more limited in horizontal extent being visible on only three of the tracklines.

Free-Air Gravity Anomaly Map

Figure 5 shows a free-air gravity anomaly map based on the data discussed previously. The root-mean-square uncertainty in the measurements is estimated to be 3.5 mgals based on an analysis of the difference in gravity readings between tracklines at crossings. The contour interval is 10 mgals.

The free-air gravity anomalies show the same subparallel relationship to the trend of the Peninsula as the bathymetric contours do. In the northeast corner of the contoured area, near Punta San Pablo, a pronounced gravity high is evident. This high is associated with the outcrop of Mesozoic rocks on the Sebastian Vizcaino Peninsula north of Punta San Pablo as is indicated by the extension of this high across

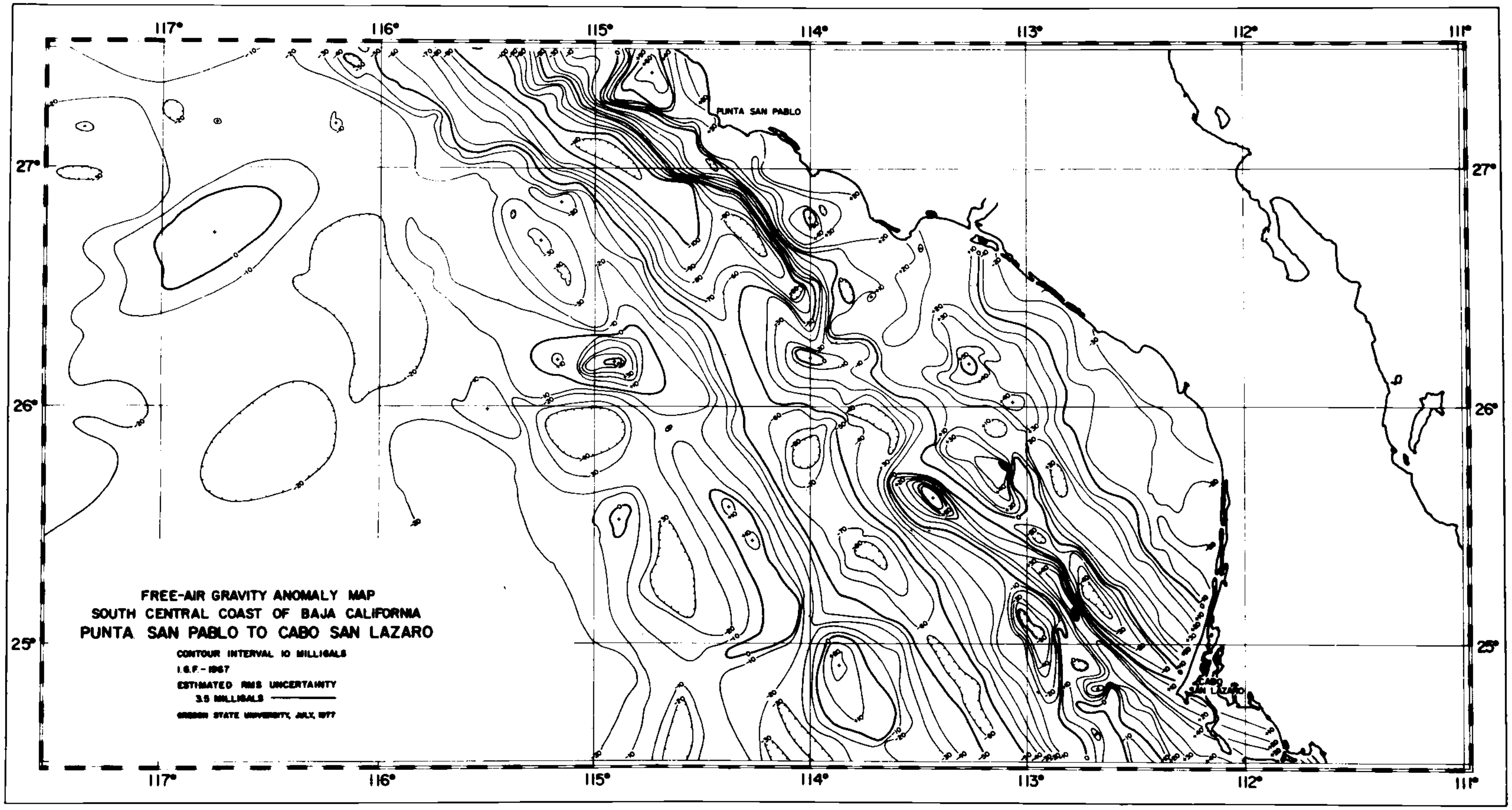

Figure 5. Free-air gravity anomaly map of the Pacific continental margin of south central Baja California.

the Sebastian Vizcaino Peninsula to 28.5° N. Lat., 115.6° W. Long. (Calderon-Riveroll, 1977). Southwest of this positive anomaly is a negative gravity anomaly which decreases to a value of approximately -113 mgals near 27.1° N. Lat., 114.9° W. Long. and is associated with the southward extension of the Cedros Trench. Near 26.7° N. Lat., 114.4° W. Long. this gravity low branches into two lobes. The eastern lobe ends near 26.4° N. Lat., 114.0° W. Long. while the western lobe continues through the area until 23.0° N. Lat., 111.3° W. Long. (Huehn, 1977), trending essentially parallel to the Baja California Peninsula. Seaward of the gravity anomaly associated with the southward extension of the Cedros Trench the anomalies generally range between 0 and -20 mgals. The +50 mgal anomalies at 26.2° N. Lat., 114.9° W. Long. and 25.6° N. Lat., 113.4° W. Long. are associated with bathymetric highs as seen in Figure 3.

Two northwest-southeast elongate positive anomalies dominate the southeastern portion of the contour map. The westernmost anomaly intersects the outcrop of Mesozoic metamorphic rock on Magdalena Island and Santa Margarita Island, south of Cabo San Lazaro. The eastern anomaly trends northwest through the area and is continuous with the gravity high associated with the outcrop of Mesozoic rock on the Sebastian Vizcaino Peninsula north of Punta San Pablo. The western anomaly is expressed in the bathymetry shown in Figure 4 as the topographic high at 480 km on trackline BB'. The striking linearity and continuity of these gravity anomalies combined with their association with Mesozoic sedimentary and metamorphic rock outcrops suggest a belt of Mesozoic rock underlying the outer continental shelf and upper slope. The -40 mgal and -50 mgal anomalies in the southeastern part of the area can be seen from the reflection profile, shown in Figure 9 and discussed later in this thesis, to be associated with sediment basins in the continental margin.

Total Magnetic Field Anomaly Map

Figure 6 shows a contour map of the total magnetic field anomalies contoured at a 100 gamma interval. The root-mean-square uncertainty in the measurements is estimated to be 60 gammas based on an analysis of the difference in magnetic field readings between tracklines at crossings.

The area around Cabo San Lazaro contains the most pronounced anomalies shown on the contour map. The anomaly high centered at 24.8^{o} N. Lat., 112.6^{o} W. Long. has a maximum value of approximately 900 gammas, while the low centered 18 km to the north decreases to approximately -300 gammas. In the southeastern part of the contour map from 25.2^{o} N. Lat., 112.8^{o} W. Long. into the coast, the magnetic anomalies generally mirror the gravity anomalies, i.e. a gravity low has a corresponding magnetic low and a gravity high has a corresponding magnetic high. Seaward of this point, corresponding

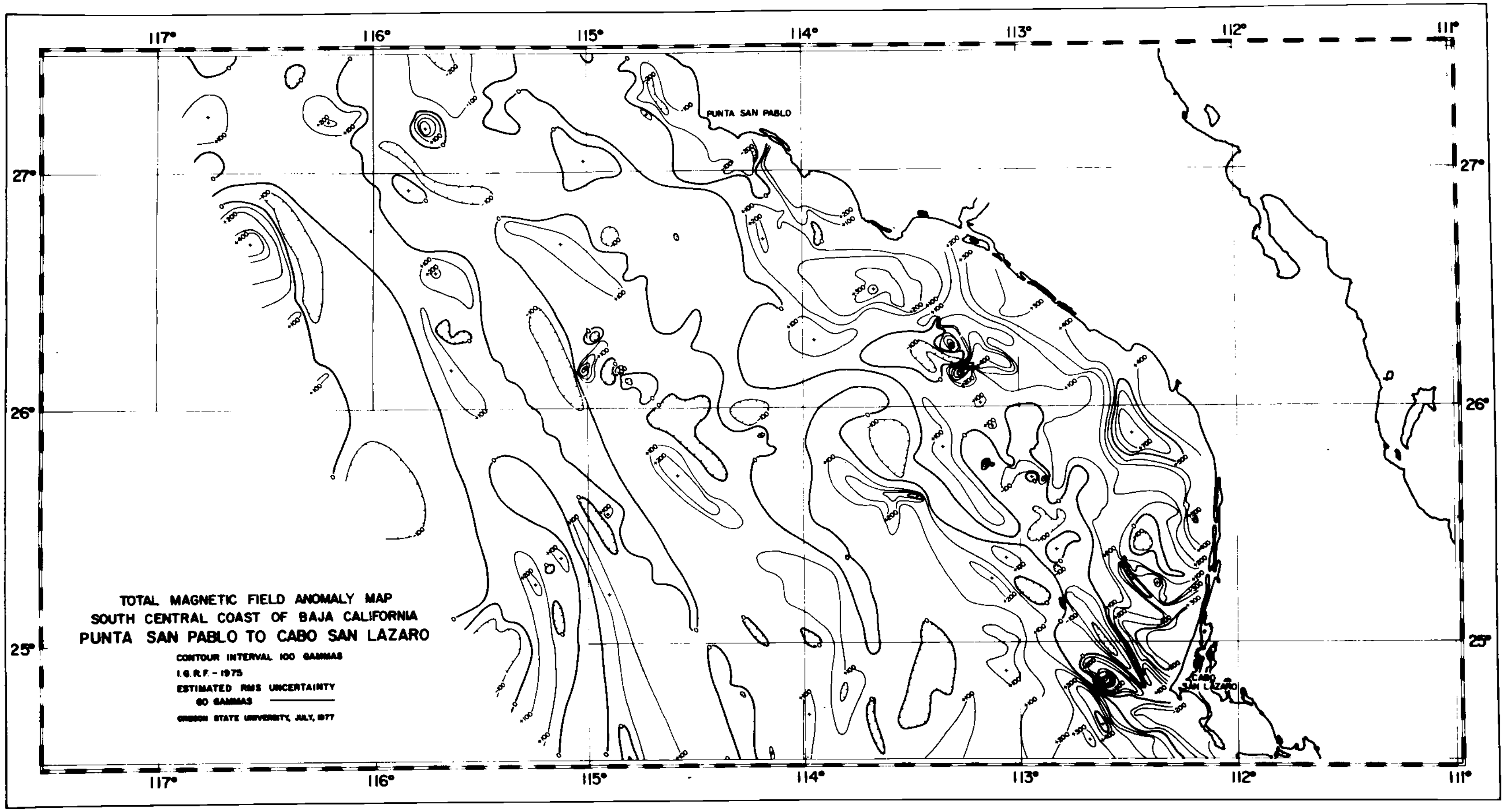

Figure 6. Total magnetic field anomaly map of the Pacific continental margin of south central Baja California.

to approximately 475 km on the cross section discussed later in this thesis, this correlation is lost. This might be interpreted as denoting a change in the magnetic character of the anomalies from induced, where the gravity and magnetic anomalies mirror one another, to remanent further seaward. One surprising feature on this map is that the gravity high associated with the Sebastian Vizcaino Peninsula that passes near Punta San Pablo is not seen in the magnetic anomaly map in the central and northern part of the contoured area. In the south-eastern section the gravity highs extending northward from Cabo San Lazaro do have a corresponding magnetic expression. This suggests a change in magnetization between the Mesozoic rock found on the Sebastian Vizcaino Peninsula and the Mesozoic rock found near Cabo San Lazaro. This is due to a change in character of the Mesozoic rock from sedimentary and meta-sedimentary on the Sebastian Vizcaino Peninsula to primarily meta-igneous around Cabo San Lazaro (Jones et al., 1976; Yeats, written communication, 1977).

Magnetic Anomaly Correlation Map

Figure 7 shows the magnetic anomalies plotted along selected tracklines. This figure is useful in investigating the continental margin because it allows for the identification of remanent magnetic lineations more easily than the contour map does. The anomaly identified as 5A is consistent with the magnetic lineations

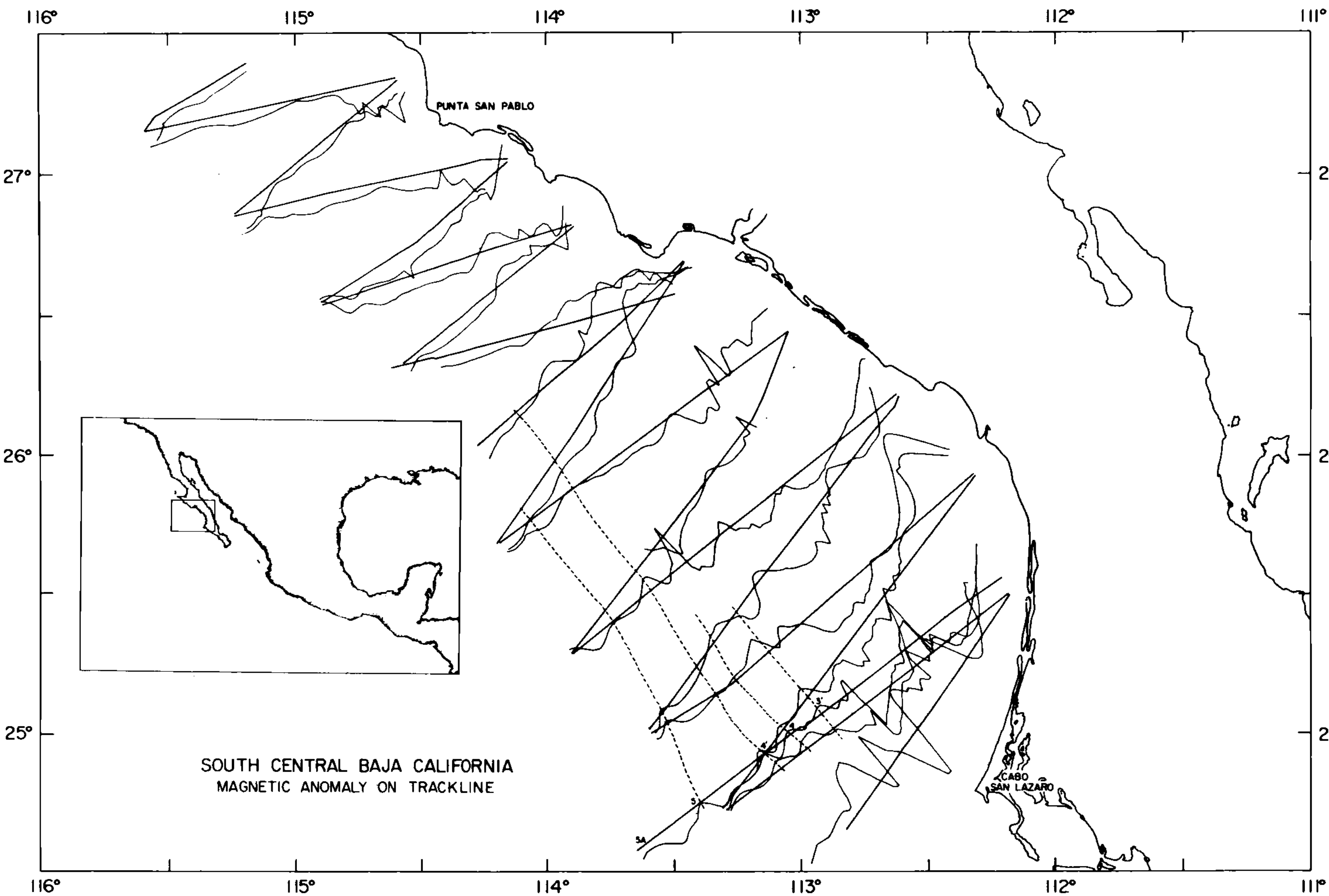

Figure 7. Total magnetic field anomalies plotted on selected tracklines across the Pacific continental margin of south central Baja California.

determined by Chase et al. (1970). The trackline on which the anomalies are identified is the trackline on which the crustal and sub-crustal cross section discussed later in the thesis is taken. The theoretical magnetic anomalies expected over a spreading center are shown in Figure 11. These theoretical anomalies were generated by program *THEOMAG written by Lu and Keeling (1974) of the School of Oceanography, Oregon State University. This program generates a theoretical magnetic profile over a spreading center taking into account the reversals of the Earth's magnetic field. As is shown in Figure 11, remanent magnetic anomalies up to anomaly 3' at 6.0 my B.P. can be identified in the observed magnetic anomalies on the trackline. The remanent magnetic anomalies can be identified on the two tracklines north and south of the trackline used for the cross section but the identification of remanent magnetic anomalies becomes very tenuous in the central and northern parts of the area. The trackline profiles in the northern part of the area are characterized by essentially flat magnetic anomalies until very close to the shoreline.

Wide Angle Reflection Line 2-76

Figure 8 depicts the travel time data and the computed structure from the reversed wide angle reflection (WAR) line 2-76. Figure 10

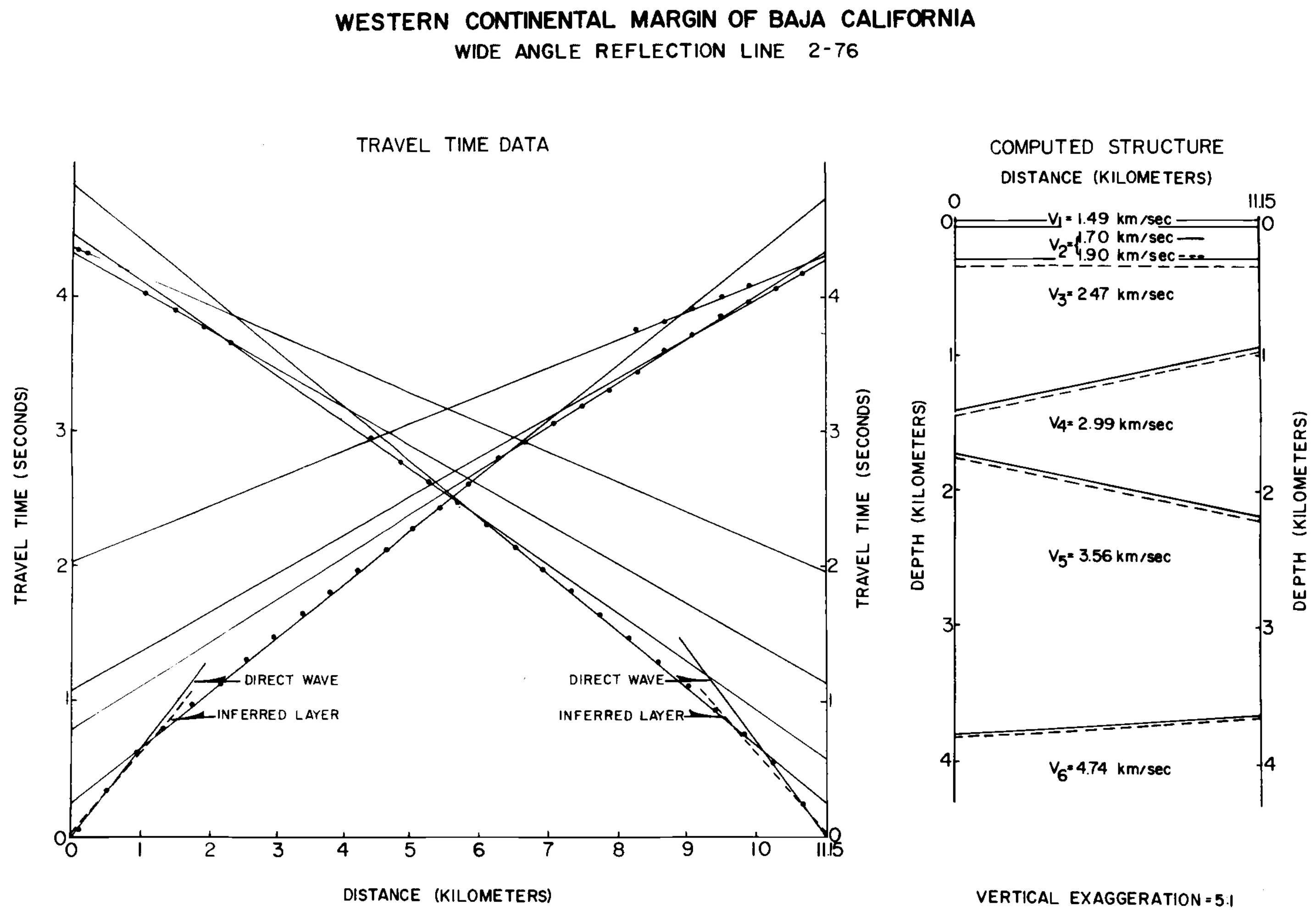

Figure 8. Travel time plot and computed structure for the reversed wide angle reflection line 2-76.

gives the location of the WAR line. The geographical coordinates of the WAR line are 25.6° N. Lat., 112.2° W. Long. Seismic noise associated with the bubble pulses of the outgoing air gun signal and also seismic noise associated with water column multiples constitute a problem in the interpretation of the records obtained along the WAR line. Reflection hyperbolas are not well enough defined to use in a systematic analysis, hence only arrivals from refracted seismic signals are used to determine the geologic structure. The reflection records taken from directly behind the ship during the acquisition of the WAR line data show no pronounced geologic structure that would interfere with the validity of the results obtained. The original records of the WAR line consist of a plot of the travel time of seismic waves from an air gun explosion to reach a sonobuoy versus the time since the ship was at the location where the sonobuoy receives the signal. Digitizing the readings and multiplying the travel time of the ship away from the sonobuoy by the ship speed yields the plot of seismic wave travel time versus distance from source.

Program *WAREFRA written by Dr. Stephen H. Johnson, School of Oceanography, Oregon State University, was used to obtain the computed structure. This program uses the Adachi relationships (Adachi, 1954) to give the depth to layers and the velocity in the layers given consistent reverse travel times. The inferred layer in Figure 8 is the ocean bottom sediment layer. The seismic noise and the high acoustic transparency of this layer make detection of the layer difficult from the air gun records. However, the bathymetric data give the depth to the top of this layer. The difference in frequency and energy between the echo sounder used for the bathymetric data and the air gun used for the WAR line makes the layer visible on the bathymetric data but not on the WAR line data. Knowing the depth to the top of this layer and assuming a velocity for the layer allows for the inclusion of the layer into the WAR line analysis. The computed structure shown by a solid line is based on a 1.70 km/sec velocity for the ocean bottom sediment layer, while the structure shown by a dashed line is based on a 1.90 km/sec velocity for this layer. At 28.8° N. Lat., 115.0° W. Long., Calderon-Riveroll (1977) obtained a value of 1.80 km/sec for the ocean bottom sediment layer based on an observed reflection hyperbola. The difference between the structures obtained from the 1.70 km/sec velocity and the 1.90 km/sec velocity is seen to be negligible.

The computed structure shows that five layers can be discerned in the upper crust. This is in good agreement with the results obtained by Huehn (1977) for WAR line 3-76 at 24.0° N. Lat., 112.2° W. Long. The velocities at the two stations were in good agreement but the depths to the layers were greater for WAR line 2-76. The upper 1.49 km/sec material corresponds to the water layer. The maximum depth of penetration for WAR line 2-76 was 3.8 km. The

Ludwig, Nafe, and Drake (1970) empirical curve again provides the means for relating the seismic velocities and layer densities. The layers can be interpreted as 1.03 gm/cc water, 2.10 gm/cc unconsolidated and semiconsolidated sediments, 2.40 gm/cc more highly consolidated sediments, and 2.67 gm/cc bedrock. In this interpretation the 2.47 km/sec and 2.99 km/sec layers have been grouped together in the 2.10 gm/cc unconsolidated and semiconsolidated sediment layer.

Seismic Reflection Line 2-76

Figure 10 shows the location of the single channel seismic reflection record obtained on the Baja-76 cruise. Figure 9 shows a line drawing from the record. The vertical scale is given in seconds of two way travel time. The horizontal scale is in kilometers and agrees with the horizontal scale of the crustal cross section discussed later in this thesis.

From the seaward end of the profile at 372 km to 394 km there is one strong reflecting surface marking the division between a highly acoustically transparent layer and the acoustic basement. The presence of many reflection hyperbolas, as would be expected from point sources, suggests that the acoustic basement is highly fractured. At 394 km the reflection record shows a structure which suggests a fault. This fault may have been caused by compressive stresses during

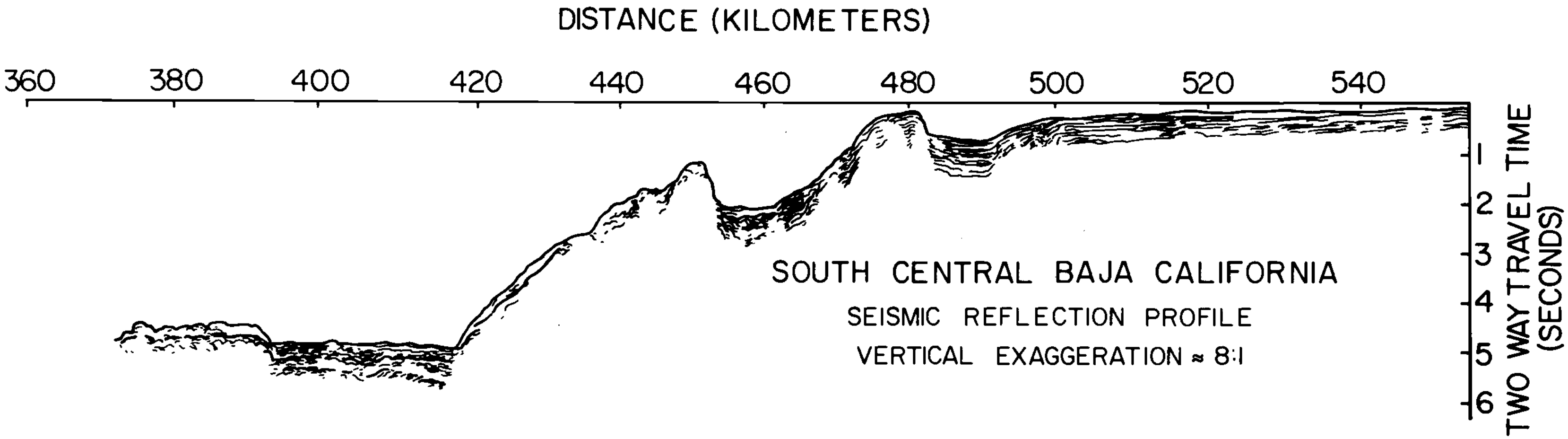

Figure 9. Seismic reflection profile BB' across the Pacific continental margin of south central Baja California. Vertical exaggeration assumes a 1.50 km/sec water velocity.

or after the period of subduction, strike-slip motion in a northwest-southeast direction as Normark (1977) has suggested to explain structures in the area, or crustal extension causing a graben structure extending from 394 km to 417 km. The reflection record from 394 km to 417 km shows two strongly reflecting horizons. The upper reflecting horizon represents a division between older deformed sediments and younger less-deformed sediments. The lower reflecting horizon represents the boundary between sediments and the acoustic basement. Below this boundary no stratification can be detected, although the presence of many reflection hyperbolas indicates a highly fractured surface. The profile between 394 km and 417 km shows a distinctively different sedimentary regime from that observed on either side of this section. The thin, very acoustically transparent layer evident both seaward and landward of this section is absent and the sediments in this section show a more highly-defined stratification and greater depth than do the sediments immediately landward or seaward. This section may provide a channel for movement of sediment essentially parallel to the coastline. From 417 km to 455 km the profile shows the ocean floor becoming shallower. The heavier line between 417 km and 435 km represents the boundary between the highly acoustically transparent layer, also visible from 394 km to the seaward end of the profile, and the underlying material. The underlying material is characterized by few internal reflecting subsurfaces.

From 453 km to 474 km the profile shows a well-developed sedimentary basin. No reflections are received from the acoustic basement. The bathymetric high centered at 480 km is associated with the outcrop of Mesozoic rock in the Cabo San Lazaro area as is seen from Figure 4 which depicts the bathymetry along the tracklines. There appear to be some internal reflectors near the top of this structure. From 484 km to 494 km the profile shows another well-developed sedimentary basin. Again, no reflections are received from the acoustic basement. From 494 km to the landward end of the profile the profile indicates sedimentary material. The seismic noise problem with water column multiples and bubble pulses becomes critical in this section because of the shallowness of the water. The structural feature responsible for the gravity high at 545 km shown on Figure 11 is not visible on the reflection record and is probably deeper than the effective depth of penetration of the seismic signals.

South Central Baja California Crustal and Subcrustal Cross Section

Figure 10 shows the location of the crustal and subcrustal cross section and the location of several constraints that bear on it. Figure 11 shows the cross section. The cross section starts at the projection of refraction station CH14, passes through the projection of refraction station CH15, WAR line 76-2, the projection of

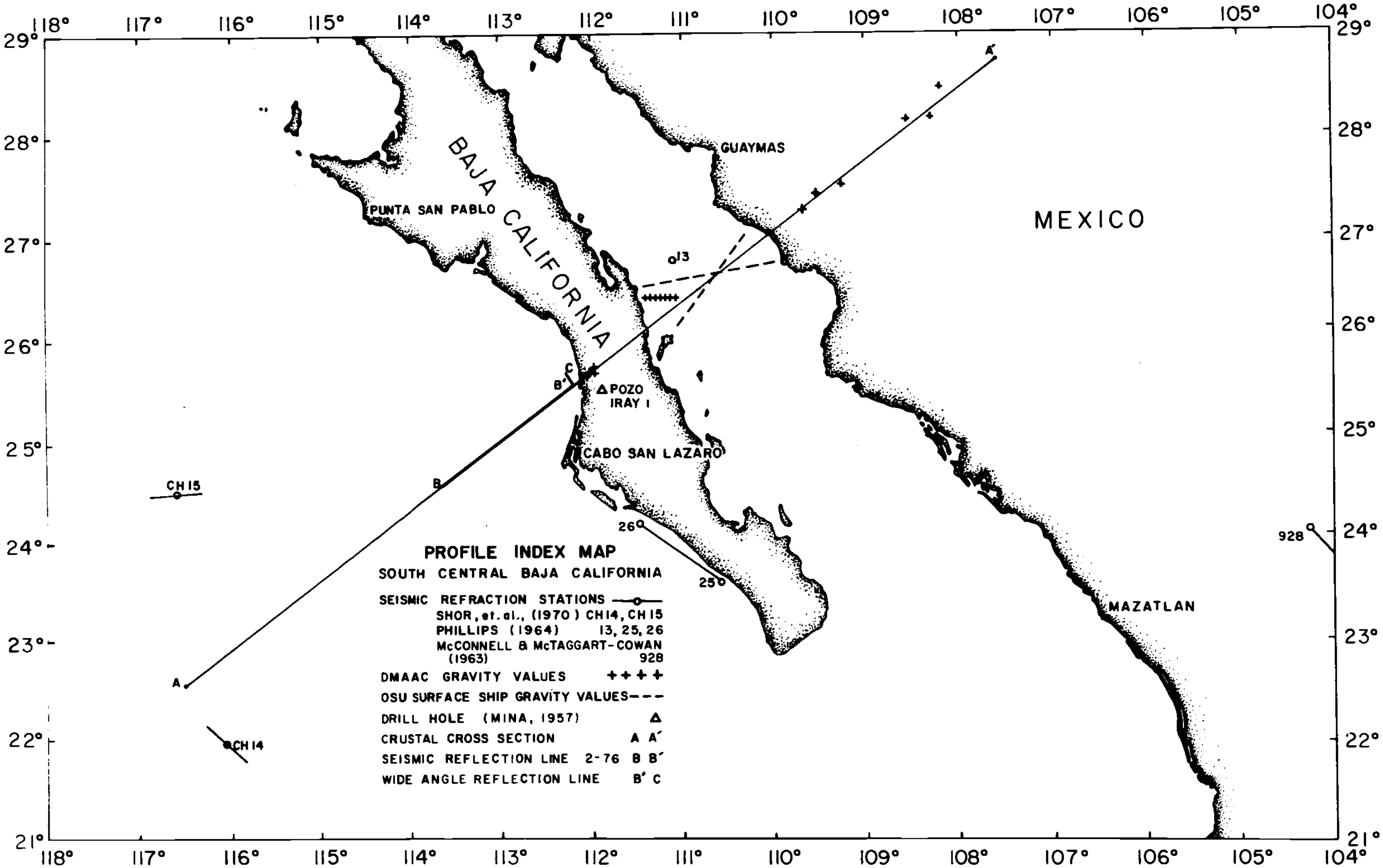

Figure 10. Index map of the location of crustal and subcrustal cross section AA', seismic reflection profile BB', wide angle reflection B'C, gravity stations in Baja, the Gulf of California and mainland Mexico, and other constraints used for the cross section AA'.

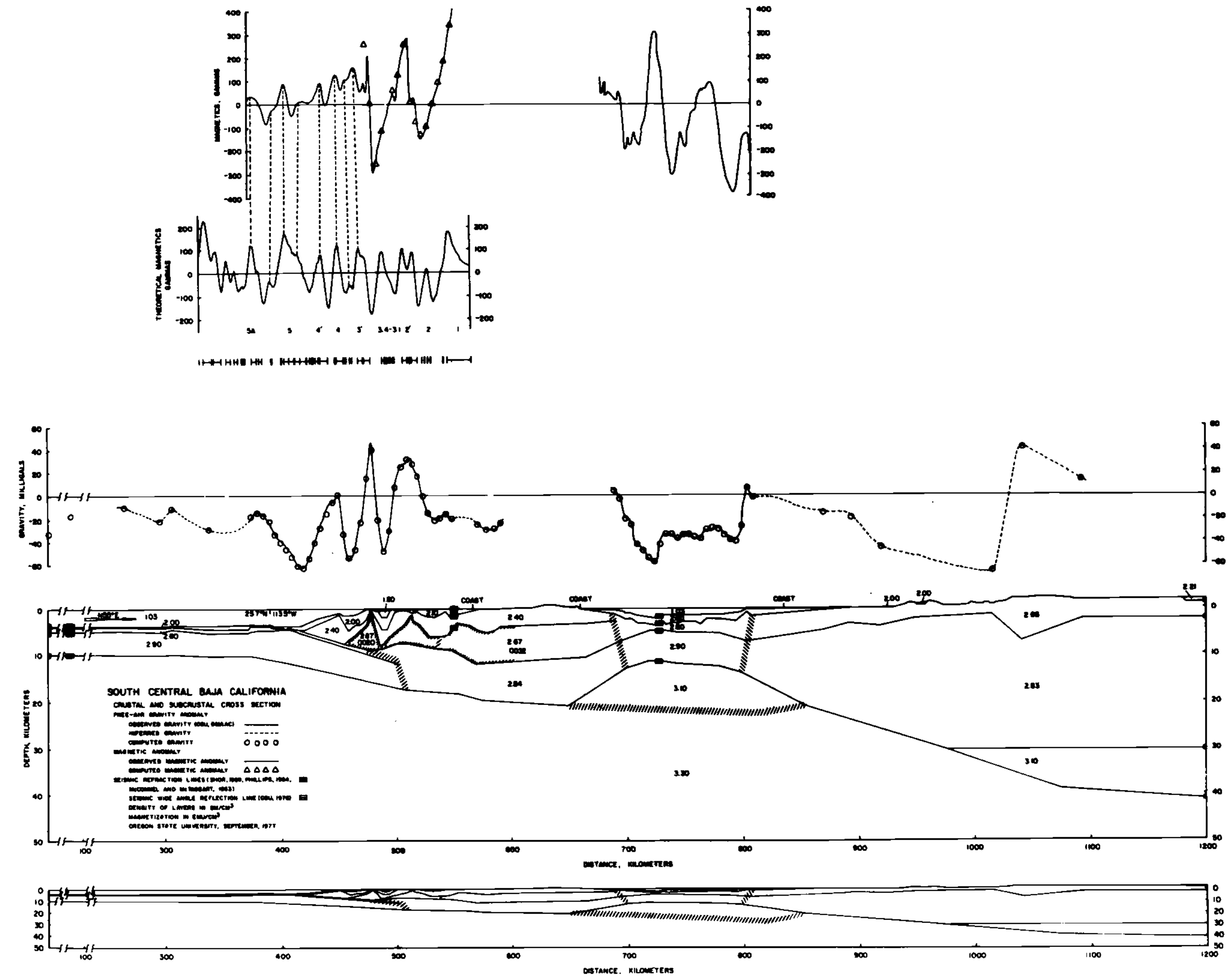

Figure 11. South central Baja California crustal and subcrustal cross section. Vertical exagerrations are 4:1 for the upper cross section and 1:1 for the lower cross section.

refraction station 13 in the Gulf of Mexico, and into mainland Mexico where refraction station 928 is used to constrain the continental end of the cross section. Barday (1974) computed a standard section for the upper 50 km of the Earth that should give approximately a zero mgal anomaly. Barday's model uses 1.03 gm/cc for the water layer, 2.00 gm/cc for the ocean bottom sediment layer, 2.60 gm/cc for a second crustal layer, 2.90 gm/cc for a third crustal layer, and 3.32 gm/cc for the mantle and gives a base value of 6442 mgal. For the model in this thesis the density of the mantle was reduced to 3.30 gm/cc to bring the computed gravity values over the refraction stations CH13 and CH14 into agreement with gravity observations by satellite (Gaposchkin and Lambeck, 1971). The first four gravity values west of the west end of the continuous gravity profile are from previous Oregon State University ship cruises. The Baja-76 trackline used for the cross section is shown as the heavier line BB' in Figure 10. This trackline starts at 372.3 km and continues to 554.4 km. The gravity values on the Baja California Peninsula and mainland Mexico are from the Department of Defense Mapping Agency Aerospace Center (DMAAC). In the Gulf of California both DMAAC and OSU surface ship data are used for the gravity anomaly profile, while the total field magnetic anomaly is obtained from OSU surface ship data only.

Shown above the cross section are the observed and computed magnetic and gravity anomalies and the theoretical magnetic anomalies. A two-dimensional approximation was used to determine the computed gravity and magnetic anomalies. The free-air gravity anomaly values were computed by the method of Talwani et al. (1959) and the total field magnetic anomalies were generated by the method of Talwani and Heirtzler (1964). Both these methods treat the structures as being infinite in extent along strike. Densities shown are in units of gm/cc and the magnetization is in units of emu/cc. Also shown above the cross section are the theoretical magnetic anomalies expected over a spreading center caused by reversals of the geomagnetic field. A half-spreading rate of 1.5 cm/yr gives an excellent agreement between the theoretical magnetic anomalies and the observed magnetic anomalies from the seaward end of the continuous magnetic profile to approximately 475 km on the cross section. Chase et al. (1970) state that at anomaly 5A time the half-spreading rate was 1.6 cm/yr north of 25^{o} N. Lat., in good agreement with the 1.5 cm/yr half-spreading rate used to generate the theoretical magnetic anomalies.

From the seaward end of the profile until 417 km the cross section shows a three-layer oceanic crust overlying mantle material. The gravity values in the section 372 km to 390 km show a gravity high seaward of the trench. This outer gravity high is often found in subduction provinces. From 417 km to 480 km the model shows two sedimentary layers having densities of 2.00 gm/cc and 2.40 gm/cc. The boundary between the layers is not visible on the reflection record. Perhaps the material under the lower continental slope has a continuous density change and the interpretation shown makes this change discrete. It could also be that the boundary between the two layers is beyond the effective depth of penetration of the seismic signal. The first magnetic anomaly modeled as an induced magnetic anomaly appears at 480 km. Pronounced bathymetric and gravity highs coincide with this magnetic anomaly. The gravity and magnetic highs necessitate an underlying rock mass with a density of 2.67 gm/cc and a magnetization of 0.002 emu/cc. The basin from 480 km to 500 km is modeled as having a depth of 7.8 km. This is not constrained by seismic control so should be considered an approximation based on reasonable density assumptions in the overlying layers. From 500 km to 525 km a gravity and magnetic high appears that is not detected in the reflection record. These anomalies are modeled by a rock mass with the same density and magnetization as used to model the gravity and magnetic anomaly highs at 480 km. The 2.40 gm/cc layer is modeled as being non-magnetic. At 540.0 km a change of magnetization but no change in density is postulated to model the high magnetic anomaly from 525 km to 550 km. The WAR line at 552 km placed a constraint on the depth to the magnetic layer and a higher magnetization facilitated the modeling. The bottom reflector at 3.8 km determined from the WAR line is taken to be the 2.67 gm/cc, 0.0032 emu/cc bedrock layer. The amount of energy available from the air gun limited the depth of penetration so that refractions were not received from the 2.83 gm/cc layer or the mantle. Seismic stations 25 and 26 (Phillips, 1964) give a depth to Moho of 19.5 km and this was used as a guide to mantle depth in this part of the cross section. In the Gulf of California a section of 3.10 gm/cc low-density mantle, as determined from a seismic velocity of 7.3 km/sec, is necessary to fit the observed gravity anomalies.

DISCUSSION

Gravity modeling and magnetic modeling are inherently non-unique as several configurations will fit the same anomaly pattern. However, the use of gravity and magnetic modeling together, the constraints imposed by the seismic reflection and seismic refraction data, and the additional constraint imposed by the mapped surface geology greatly reduce the non-uniqueness of the interpretation. The cross section shown in Figure 11 can be interpreted geologically as shown in Figure 12.

West of 417 km the three-layer oceanic crustal structure is retained. The sediment-filled trench, which corresponds to the southward extension of the Cedros Trench, extends from 394 km to 417 km. The bathymetric, gravity, and magnetic highs and the features in the seismic reflection record indicative of faulting such as at 394 km, may have been caused or accentuated by compressive stresses during or after the period of active subduction on the Pacific side of the Baja California Peninsula. Alternatively, Normark (1977) suggests that the structures observed on single-channel air gun records may have been caused by strike-slip faulting in a northwest-southeast direction. However, the striking similarity between the seismic reflection profile BB' and reflection profiles obtained across convergent plate margins (Ross and Shor, 1965; Kulm and Fowler, 1974) suggest that

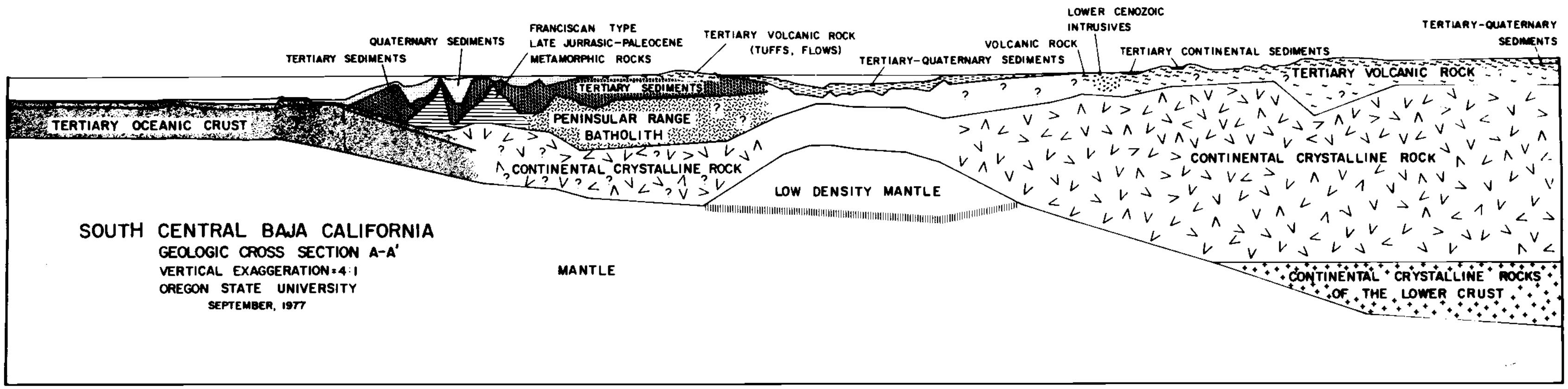

Figure 12. Geologic interpretation of crustal and subcrustal cross section AA'.

in large part the structures observed on the continental margin were formed during the period of active subduction.

The 2.40 gm/cc rock mass underlying the lower slope may represent an accretionary prism composed of material scraped from or broken off the subducting slab and accreted as imbricate thrust sheets. The interpretation of the 2.67 gm/cc, 0.002 emu/cc block as Franciscan-type rock is fairly certain because of the outcrops of this rock type on the islands around Cabo San Lazaro and on the Sebastian Vizcaino Peninsula north of Punta San Pablo. The distinctive linearity of the gravity anomalies supports this interpretation. The 0.002 emu/cc magnetization would be a very high magnetization for meta-sedimentary rock. However, the rocks on Santa Margarita Island and Magdalena Island contain highly magnetic greenschists and serpentine (Yeats, written communication, 1977) which would produce the higher magnetization. The 2.67 gm/cc density is well within the range of metamorphic rock.

The change in susceptibility from 0.002 emu/cc to 0.0032 emu/cc may indicate a change from Franciscan-type rock to rock associated with the Peninsular Range batholith. This rather small change in magnetization would be slim evidence on which to base this transition if it were not for the outcrops of Mesozoic intrusive rock at the tip of the Baja California Peninsula and in the area above 28° N. Lat. The intrusive rocks in these two areas fall in the same time span determined by K/Ar dating (Krummenacher and Gastil, 1970) and also are included in the gabbroic subbelt of the batholith suggesting similar compositions (Gastil and Jensky, 1973). The 0.0032 emu/cc magnetization is in the range of quartz diorite but it is a fairly high value. An alternative interpretation of this 2.67 gm/cc, 0.0032 emu/cc block is that it is composed, in part, of the Great Valley and Sierra Foothills type eugeosynclinal and miogeosynclinal basement of oceanic crust (Jones et al., 1976; Yeats, personal communication, 1977). The Franciscan Formation abuts against rocks of this type to the east in south central California. Perhaps the same pattern continues into Baja California.

The 2.40 gm/cc layer overlying the 2.67 gm/cc block is interpreted as Tertiary sedimentary rock with a cap of volcanic rock representing the Comondu Formation. The block is modeled as being non-magnetic under the upper continental slope. This may seem unjustified considering the large amount of Tertiary volcanic rock shown on the geologic map. However, the geologic map shows a strip of Tertiary sediments on the western edge of the Peninsula and a drill hole at 25.5° N. Lat., 111.9° W. Long. reported by Mina (1957) shows a lithology of shale, sandstone, and conglomerate down to a depth of 3.0 km. This type of lithology would contribute negligibly to the magnetic anomaly. Another verification of the fact that the 2.40 gm/cc layer contributes negligibly to the magnetization is the fact that the local gravity high observed at 545 km does not have a corresponding signature in the magnetic anomaly. The wavelength of this gravity anomaly implies that its source is close to the surface. If the upper 2.40 gm/cc layer had a noticeable magnetization, the structure causing the gravity anomaly would also disturb the magnetics.

The 2.85 gm/cc layer underlying the 2.67 gm/cc layer can be interpreted from two contrasting viewpoints. If it is assumed that the movement of the East Pacific Rise from the Pacific side of the Peninsula to the Gulf of California occurred as a discrete jump, then the 2.85 gm/cc layer could be interpreted in large part as continental crystalline rock related to the 2.83 gm/cc density material underlying mainland Mexico with perhaps a contribution from oceanic crust associated with the Farallon Plate. The Farallon Plate would have been thrust under the Peninsula during the period of subduction. If it is assumed that the East Pacific Rise remained active as it was overrun by the continent, then the 2.85 gm/cc material could be interpreted as representing a combination of 2.90 gm/cc oceanic crust and 2.60 gm/cc oceanic crust or as an area of intermixing between oceanic and continental crust. The author prefers the first explanation because of the spreading rates used to generate the theoretical magnetic anomalies. The last recognizable anomaly on the continental shelf is the 6 my B.P. 3' anomaly. The fact that this anomaly is recognizable more than 60 km landward from the start of the slope would seem to suggest that the ridge was active underneath the continent. However, to traverse the distance from this anomaly at 470 km on the crustal cross section to where spreading is presently occurring in the Gulf, taken as 730 km on the crustal section, in six million years requires a 4.3 cm/yr half-spreading rate. The half-spreading rate used to match the observed magnetic anomalies is 1.5 cm/yr which agrees well with the half-spreading rate of 1.6 cm/yr north of 25^{o} N. Lat. at anomaly 5A as determined by Chase et al. (1970). Chase et al. (1970) also mapped the magnetic anomaly bands southwest of the tip of the Baja California Peninsula where the anomalies are continuous from anomaly 6 to the present and found that from anomaly 3 at 5 my B.P. to the present center of the East Pacific Rise requires a half-spreading rate of 2.4 cm/yr. There is no evidence southwest of the Baja California Peninsula of a greatly increased spreading rate between 5 my B.P. and the present. Moore (1968) states that the present half-spreading rate in the Gulf of California is 3.0 cm/yr based on the remanent magnetic anomalies observed at the mouth of the Gulf. Hence to state that the East Pacific Rise remained active as it subducted is to postulate an increased spreading rate around 26^{o} N. Lat. that is not visible in the areas where the anomalies are continuous.

In the Gulf of California the geophysical data suggest an oceanic character for the Gulf floor. The high heat-flow values, the bathymetric and magnetic lineaments, and the shallow, strike-slip seismicity all impart an oceanic character to the Gulf. The 3.10 gm/cc block is interpreted as representing low-density mantle associated with the high heat-flow values.

CONCLUSIONS

This work corroborates many of the theories set forth concerning the Baja California Peninsula. The free-air gravity anomaly map shows the anomalies expected over a subduction zone province. A well-developed trench, continental slope, and continental shelf topography, a well-pronounced gravity low associated with the trench axis, and gravity lows associated with basins developed on the continental slope are consistent with this area being a relic subduction zone. The structures seen in the reflection record may be influenced by strike-slip faulting as suggested by Normark (1977), however, the striking similarity between seismic reflection profile BB' and seismic profiles obtained by Ross and Shor (1965) and Kulm and Fowler (1974) across convergent plate margins suggest that the structures were formed mainly during the period of subduction on the Pacific side on the Baja California Peninsula.

The correlation between the observed magnetic anomalies along trackline BB' used for the cross section and the theoretical magnetic anomalies expected over a spreading center as seen in Figure 11 shows that remanent magnetic anomalies can be identified 60 km landward of the start of the continental slope. Anomalies can be identified as young as 6 my B.P. on the Pacific side of the south central Baja California Peninsula. This refutes the statements of

Atwater (1970) and Chase et al. (1970) that subduction ceased off south central Baja California at approximately 11 my B.P. From an examination of the magnetic anomalies and the distance across the Baja California Peninsula it appears unlikely that spreading on the East Pacific Rise alone is sufficient to account for the movement of the Rise into the Gulf of California. This would require the half-spreading rate to average 1.5 cm/yr from anomaly 5A at 12 my B.P. to anomaly 3' at 6 my B.P. and then increase to 4.3 cm/yr from anomaly 3' to the present. The present half-rate of spreading at the mouth of the Gulf of California is estimated at 3.0 cm/yr (Larson et al., 1968). There is no evidence of an increased spreading rate southwest of the tip of Baja California where the remanent magnetic anomalies generated by the East Pacific Rise are continuous from anomaly 5A to the present (Chase et al., 1970).

The geologic interpretation of the crustal cross section shows the Pacific continental margin of the Baja California Peninsula as composed of Quarternary and Tertiary sediments and sedimentary rock, Franciscan-type metamorphic rock, and rock that may form a part of the Peninsular Range batholith or alternatively at least in part be associated with the eugeosynclinal basement observed in south central California. The interpretation of the 2.67 mg/cc, 0.002 emu/cc material as Fransican-type rock is fairly certain because of the continuity of the free-air gravity anomalies from the islands around

Cabo San Lazaro where Franciscan-type rocks outcrop. It appears likely that the 2.67 gm/cc, 0.0032 emu/cc block represents the Peninsular Range batholith because of the outcrops of this type rock both north and south of the area. The outcrops both north and south of the area belong to the gabbroic subbelt of the batholith (Gastil and Jensky, 1977) and are contemporary as determined by K/Ar dating (Krummenacher and Gastil, 1970).

In the Gulf of California the geologic cross section shows an area of low-density mantle. This corresponds to a 3.10 gm/cc block needed to yield a model which agrees with the observed free-air gravity anomalies as shown in Figure 11 and the low seismic velocity of the mantle observed in the area (Phillips, 1964).

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