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Title: CRUSTAL STRUCTURE OF THE TEHUANTEPEC RIDGE AND ADJACENT CONTINENTAL MARGINS OF SOUTHWESTERN MEXICO AND WESTERN GUATEMALA

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A free-air gravity anomaly map of the area between 10°-17°N and 90°-101°W shows distinctive positive and negative anomalies which parallel the Tehuantepec Ridge. The positive anomaly approximately overlies the topographic expression of the ridge. On the wide continental shelf southeast of the Gulf of Tehuantepec a positive gravity anomaly with an amplitude in excess of +100 mgal parallels the coast for most of its length and turns abruptly inland at its northern end. A crustal and subcrustal cross section constrained by gravity, magnetic, seismic reflection and seismic refraction data and oriented normal to the Guatemala continental margin indicates the positive shelf anomaly is primarily the result of a relatively shallow $2.62\ g/cm^3$ density block which may be continuous with and genetically similar to the rocks of the Nicoya Complex on the Nicoya Peninsula, Costa Rica. A crustal and subcrustal cross section normal to the

continental margin off southern Mexico northwest of the Tehuantepec Ridge shows a shelf structure which is very different from the continental margin off Guatemala. This suggests different tectonic interactions at the convergent plate boundaries on opposite sides of the ridge.

The Tehuantepec Ridge, in a crustal and subcrustal cross section oriented normal to its trend, is shown to occur at the juncture of two oceanic crusts of different structure and age. Southeast of the ridge in the Guatemala Basin the crust is about 9.5 km thick and northwest of the ridge the crust is about 12 km thick. Hence the Tehuantepec Ridge is essentially a fracture zone, but because its orientation is oblique to present plate motions and it is aseismic, it is concluded to be a relic fracture zone.

Crustal Structure of the Tehuantepec Ridge and Adjacent Continental Margins of Southwestern Mexico and Western Guatemala

by

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CRUSTAL STRUCTURE OF THE TEHUANTEPEC RIDGE AND ADJACENT CONTINENTAL MARGINS OF SOUTHWESTERN MEXICO AND WESTERN GUATEMALA

INTRODUCTION

The Tehuantepec Ridge, a linear range of submarine mountains oriented about N40°E on the Cocos lithospheric plate, intersects the Middle America Trench near 15°N 95.5°W. It can be traced for about 400-500 km seaward from the trench where its relief becomes subdued and its location obscure. There are a number of distinct changes in the trench topography where the ridge intersects the trench (Fisher, 1961). Farther seaward the ridge separates large basins which differ in depth by about 450 meters. Many theories exist concerning the origin of the Tehuantepec Ridge. These include a fracture zone (Menard and Fisher, 1958), a hot spot trace (Herron, 1972) and a hinge fault (Truchan and Larson, 1973).

During 1969, 1971 and 1973 cruises the Oregon State University R/V YAQUINA collected gravity, magnetic and seismic reflection data in the vicinity of the Tehuantepec Ridge. These data constitute the primary data used in this study.

The purpose of this study is to determine the structure of the Tehuantepec Ridge and adjacent continental margin and to consider the hypotheses concerning the origin of these features.

PREVIOUS WORK

Bathymetric

The first generally available bathymetric chart of the region immediately west of Central America was published by Alexander Agassiz (1906) in the general report of the 1904-1905 expedition of the U.S. Fish Commission steamer ALBATROSS. Although the Tehuantepec Ridge is not recognized on this chart, the Guatemala Basin is remarkably well defined based on six soundings. Also included on the map are the Acapulco Deep and Guatemala Deep, two very deep troughs relatively close to shore which coincide approximately with portions of the present Middle America Trench (see Figure 1).

Shortly after 1920 the U.S. Navy initiated a program of regular deep-sea soundings by vessels en route from port to port which resulted in the publication of a revised bathymetric chart of the region (Whitcroft, 1944). This chart shows that the Guatemala Deep extends much farther north and its depth is accurately given as greater than 3500 fathoms (6401 m) based on soundings by the U.S. Coast and Geodetic Survey Steamer GUIDE in 1923. The near shore depression off the coast of Central America is described as a "practically continuous trough" (Whitcroft, 1944), but the Mexican

Trough to the north of the Gulf of Tehuantepec and the Central American Trough to the south are regarded as separate features. This distinction is made because the 2000 fathom (3658 m) contour, which was considered to be the trough boundary, does not quite connect near 15°N 96°W. The northwestern boundary of the Guatemala Basin is more accurately located and the 988 fathom (1807 m) peak near 13°N 97°W is included. This peak, discovered by the EMDEN in 1935 is still the shallowest point known on the Tehuantepec Ridge.

As late as 1955 the Tehuantepec Ridge was still missing from the most up-to-date bathymetric charts of the ocean bottom west of Central America (Heacock and Worzel, 1955). In its place is the Albatross Rise, a much wider feature centered about 250 km northwest of the actual location of the ridge. The Albatross Rise had roughly the same trend as the present Tehuantepec Ridge, but lacked the high peaks now known to exist. There was one very significant change on the Heacock and Worzel (1955) chart not contained on previous maps of the area, namely that the Middle America Trench was mapped as a continuous feature. Also noted in the text accompanying their chart is the relationship between this trench and a belt of shallow- and intermediate-depth earthquakes and a parallel line of volcanoes on the adjacent continent (Heacock and Worzel, 1955).

The earliest comprehensive discussion of the Tehuantepec Ridge is that of Menard and Fisher (1958). Because the discovery of this

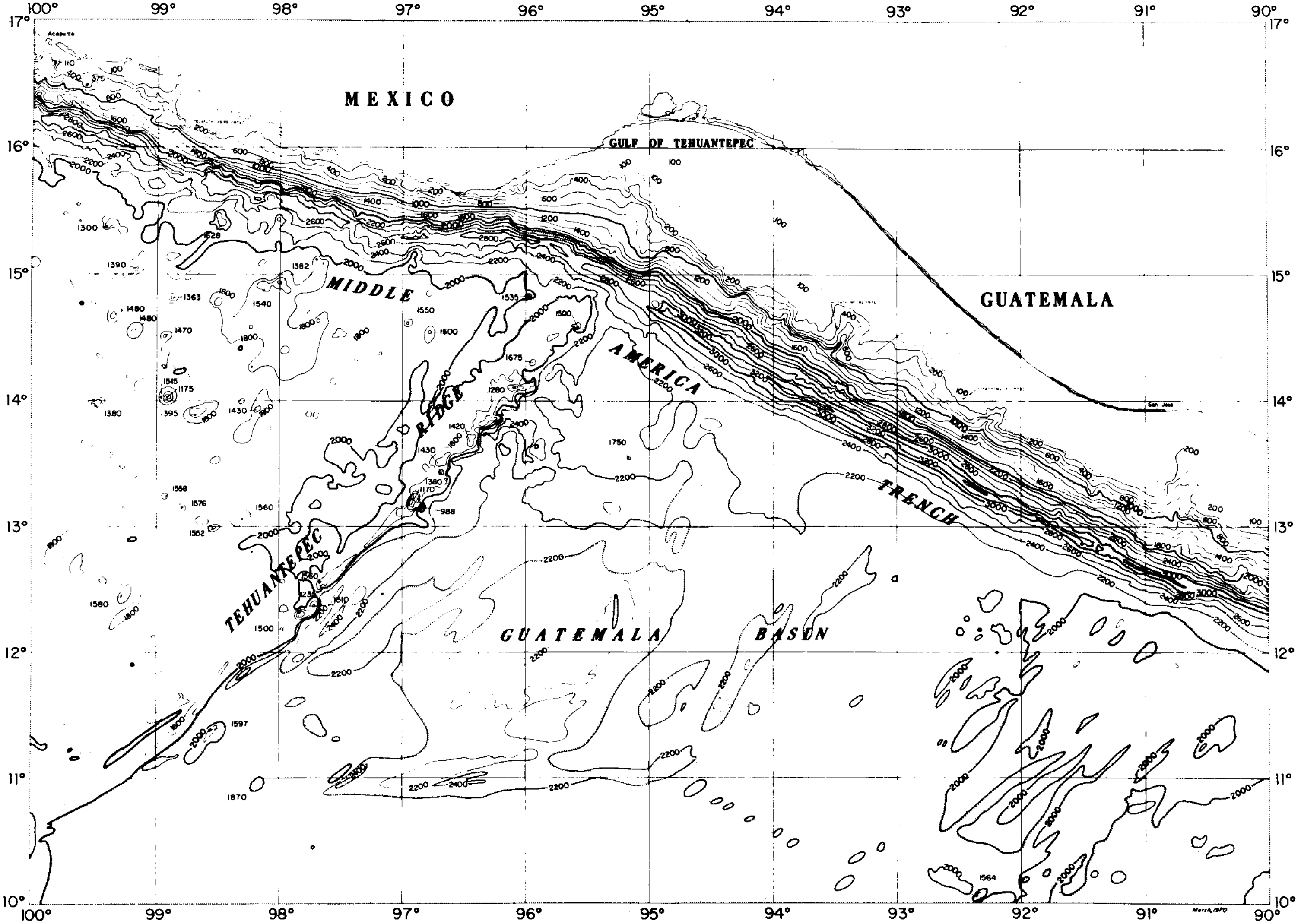

Figure 1. Bathymetric map of the Tehuantepec Ridge area. Contour interval = 200 fathoms with 100 fathom contour dashed where applicable.

ridge occurred in conjunction with the exploration of the Clipperton Fracture Zone and because the two features apparently meet near 10°N 101°W they were originally thought to be continuous. They found by comparison that the topography of the Tehuantepec Ridge is similar to the typical northeastern Pacific fracture zone topography. They also noted the unique trend of the ridge--supposedly the first fracture zone not parallel to the other known fracture zones of the eastern Pacific--and its short radius of curvature.

Three more recent bathymetric charts of the Tehuantepec Ridge area (Fisher, 1961; Chase, 1968; USNOO, 1971) are more detailed than that of Menard and Fisher (1958), but show no new features. This study used the most recent map contained in the Bathymetric Atlas of the Northeastern Pacific Ocean (USNOO, 1971).

Figure 1, a bathymetric map of this study area, indicates the Tehuantepec Ridge is a linear range of mountains separating large areas which differ in depth by about 250 fathoms (457 m). For most of its length elongate depressions parallel both sides. The northwestern most depression is relatively wide, about 60 km, and is approximately 100-150 fathoms (183-274 m) deeper than the regional depth farther to the northwest (Fisher, 1961). The depression southeast of the ridge is narrower, about 30 km, and is approximately 150-250 fathoms (274-457 m) deeper than the regional depth in the Guatemala Basin (Fisher, 1961). The ridge is asymmetrical, with the southeastern flank considerably steeper than the northwestern flank. The larger peaks reach depths of 1200-1500 fathoms (2195-2743 m) and most of the rest of the ridge is at depths shallower than 1800 fathoms (3292 m).

There are a number of marked changes in topography where the Tehuantepec Ridge intersects the Middle America Trench near 15°N 95.5°W. North of the intersection the trench is flat bottomed and generally reaches depths of 2500-2900 fathoms (4572-5304 m). South of the intersection, however, the trench bottom is more V-shaped and reaches depths of 3000-3500 fathoms (5486-6401 m). There is a slight bend in the trench, concave to the southwest, and the trench is slightly constricted right at the ridge-trench intersection.

The continental shelf is almost non-existent to the northwest of the Gulf of Tehuantepec but is about 100 km wide to the southeast. Also notable is the presence of a double shelf break (Fisher, 1961) in the Gulf of Tehuantepec, indicated by the 100 fathom (183 m) contour of Figure 1.

Seismic

The structure of the continental shelf southeast of the Gulf of Tehuantepec detailed by seismic reflection profiles appears to include a large synclinal structure with at least 2 km of sediment fill near 15.5°N 94.5°W (Ross and Shor, 1965). The seaward boundary of the syncline is a large acoustically opaque mass located under the seaward edge of the continental shelf, and the landward dip of the sediment layers suggests the structure extends landward of the coast. There is no evidence indicating synclinal structure under the narrow continental shelf northwest of the Gulf of Tehuantepec except at the very northern end of the Middle America Trench where sediments are ponded landward of an outer shelf basement high. Ross and Shor (1965) propose this outer shelf high to be the southern extension of the Islas Trés Marias.

Seismic reflection profiles of the Tehuantepec Ridge (Truchan and Larson, 1973; Figure 3) show it lacks a significant sediment cover except in local depressions where sediment is ponded. The ocean floor in the surrounding region is generally covered with draped sediments about 300 meters thick southeast of the ridge and about 100 meters thick northwest of the ridge. The sediments, apparently of pelagic origin, include many ash layers whose source is apparently the volcanoes on the adjacent continent (Bowles et al., 1973).

As a part of the 1954 Acapulco Trench Expedition personnel of Scripps Institution of Oceanography (SIO) occupied seven seismic refraction stations in and near the Middle America Trench (Shor and Fisher, 1961). Four of these stations plus an additional station also occupied by SIO personnel later in the same cruise (see Figure 6 and Table 1) are used in the construction of the crustal and subcrustal cross sections discussed in Chapter III. The refraction stations in the trench indicate the Mohorovicic Discontinuity (Moho) southeast of the Gulf of Tehuantepec is about 15 km deep and the Moho northwest of the Gulf of Tehuantepec is about 11 km deep. A profile of three refraction stations perpendicular to the trench near 13°N shows thinner than average crust (8.1 km) just seaward of the trench thickening to 14.8 km and 16.5 km under the trench and continental shelf, respectively.

Gravity

Vening Meinesz (1948; Heiskanen, 1939) made the first gravity measurements in the vicinity of the Tehuantepec Ridge. These measurements, which include a four point gravity profile of the Middle America Trench and adjacent continental slope near 98.3°W, were interpreted by Vening Meinesz (1948) as indicating a land-block overriding a sea-block. He also noted an apparent lack of local isostatic compensation in the region.

Two later cruises, one by the USS CHOPPER in 1949 and one by the USS BERGALL in 1950, collected submarine pendulum data near the Tehuantepec Ridge (Worzel, 1965). Both of these cruises occupied gravity stations at approximately 50 mile intervals with a 100 mile gap after each fifth station. Figure 2 includes and locates a total of 25 gravity values from these two cruises. Onshore gravity values compiled from Central American sources and listed in the Department

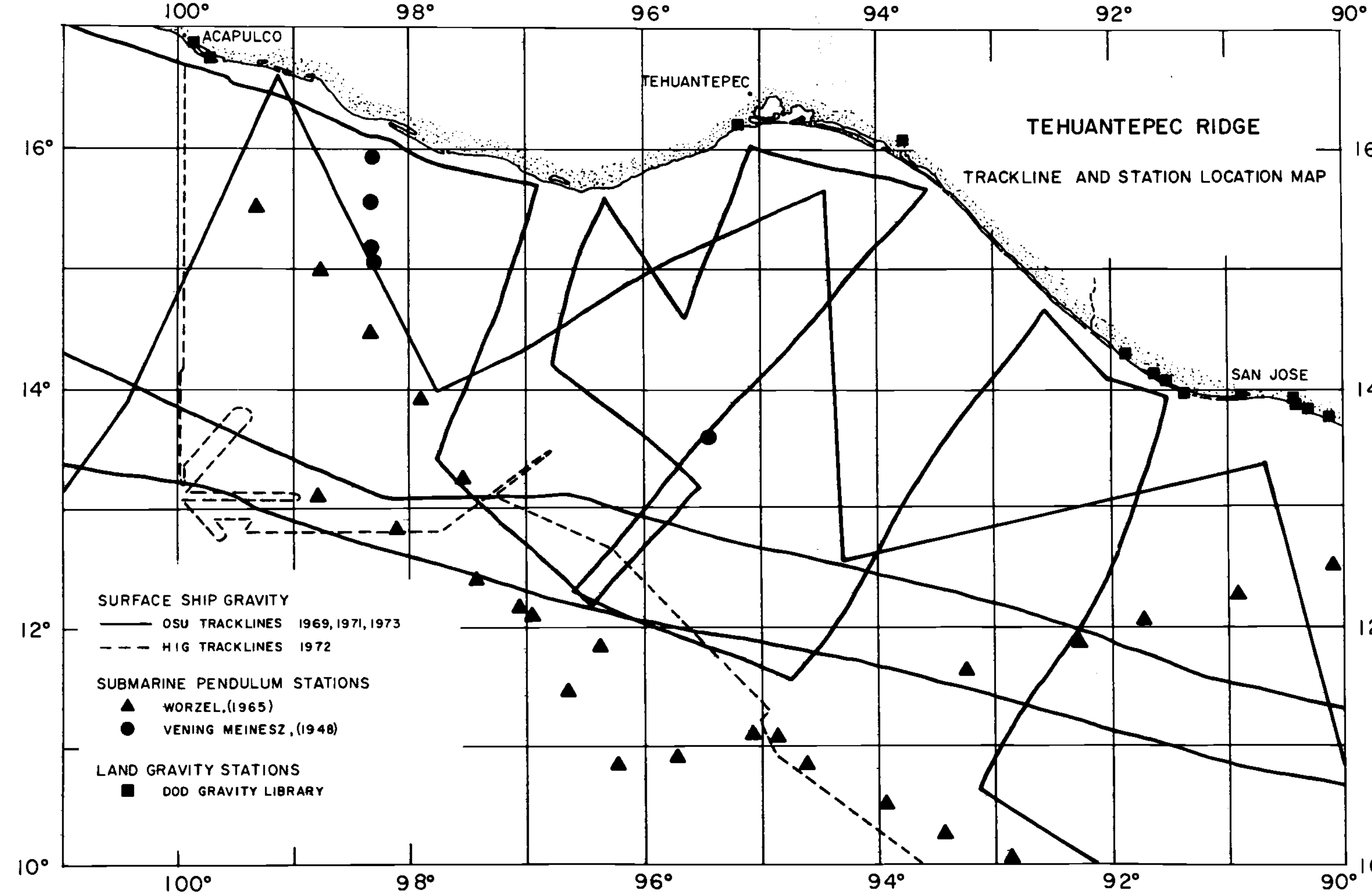

Figure 2. Location map of surface ship gravity tracklines, submarine pendulum stations and land gravity stations.

of Defense Gravity Library are also used in this study and are indexed in Figure 2.

Data obtained on cruises of the Oregon State University R/V YAQUINA during 1969, 1971 and 1973 constitute the majority of the data used for analysis in this study. Figure 2 shows the locations of the OSU tracklines along which gravity, magnetic and seismic reflection measurements were made. Also included in Figure 2 is the trackline of a gravity profile made by the Hawaii Institute of Geophysics vessel KANA KEOKI in 1972.

Magnetic

The first large scale study of magnetic anomalies in the East-Central Pacific (Herron, 1972) resulted in the correlation of many anomalies generated at spreading centers but failed to recognize any anomalies in the Guatemala Basin. From crustal spreading at the East Pacific Rise, magnetic anomalies are correlated out to about 10 my (anomaly 5) both north and south of the Siqueros Fracture Zone, which offsets the East Pacific Rise near 8°N 103°W. Anomalies are also tentatively correlated out to approximately 38 my (anomaly 13) just south of the Guatemala Basin. A later study (Lewis *et al.*, 1975; W. Lynn, personal communication) which focuses attention on the region north of the Tehuantepec Ridge and east of the East Pacific Rise, noted a fanning of magnetic anomalies to an orientation of about

N40°W near the Middle America Trench. Correlation of magnetic anomalies north of the ridge (see Figure 8) indicates a crustal age of approximately 14 my just seaward of the trench. Hence, on the basis of magnetics the region just north of the Tehuantepec Ridge appears to be consistent with plate tectonic concepts with crust created along the East Pacific Rise and subducted along the Middle America Trench. Over the Guatemala Basin the amplitude of the magnetic anomalies is low (Anderson, 1974) and none have been correlated with theoretical anomalies.

Heat Flow

Heat flow measurements in the Guatemala Basin indicate that it is a region of anomalously low values (VonHerzen and Uyeda, 1963; Langseth et al., 1965; Vacquier et al., 1967). The average heat flow through the sea floor in this area is approximately 0.79 $\mu cal/cm^2/sec$ (Vacquier et al., 1967) or about half the average oceanic heat flow and Vacquier et al. (1967) conclude that a mantle deficient in radioactive heat sources is necessary to account for this observation. Two processes have been suggested (Vacquier et al., 1967) by which a mantle of this type can be obtained under the Guatemala Basin. If the Central American continent had been situated in the Guatemala Basin when vertical differentiation of the rocks took place it would leave behind a mantle deficient in radioactive materials when it moved.

The second hypothesis suggests that if horizontal differentiation took place, the mantle under the regions surrounding the Guatemala Basin could have its radioactive content enhanced at the expense of the mantle under the basin itself. Both of these theories, however, lack supporting evidence. Alternatively, Anderson (1974) suggests that this portion of the Cocos Plate passed over the downgoing limb of a convection cell, or "cold spot," between 25 and 40 my ago and that the effect of this lack of heat input is now being measured in the Guatemala Basin.

DATA INTERPRETATION

Seismic Profiles

Figure 3 is a line drawing of the seismic reflection profile which corresponds to the Tehuantepec Ridge crustal and subcrustal cross section (Figure 9 and profile CC' of Figure 6). The depth scale is based on an assumed velocity of 1.5 km/sec for the velocity of sound in water and hence is used only to estimate relative differences in water depth and not for sediment thicknesses. The Tehuantepec Ridge is evident in this profile as a hill without sediment cover, rising about 600 to 700 meters above the adjacent sea floor. Just southeast of the ridge the sediment cover is very sparse except in local depressions where sediment has ponded, and at a distance of about 60 km from the ridge the sediment reaches a maximum thickness which remains approximately constant to point C near 11.5°N 94.7°W. Northwest of the ridge the sediment thickness increases away from the ridge to point A near 13.3°N 97.8°W, and may continue to increase beyond that point. The sediments in this profile are generally acoustically transparent and draped over basement topography suggesting a pelagic or hemipelagic origin.

Figure 4 shows three line drawings of seismic reflection profiles across the Middle America Trench. Normal faulting in the upper

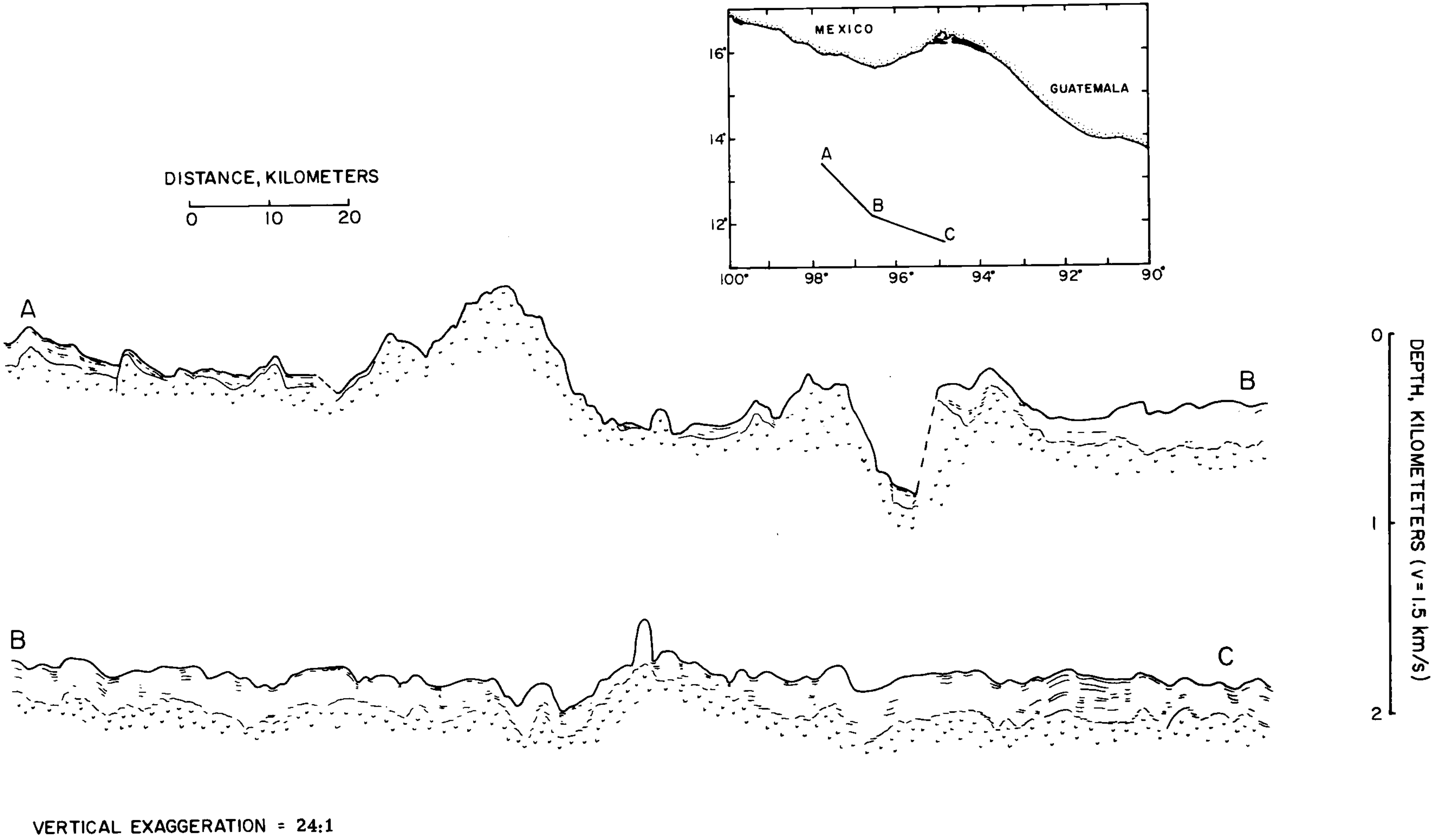

Figure 3. Seismic reflection profile across the Tehuantepec Ridge.

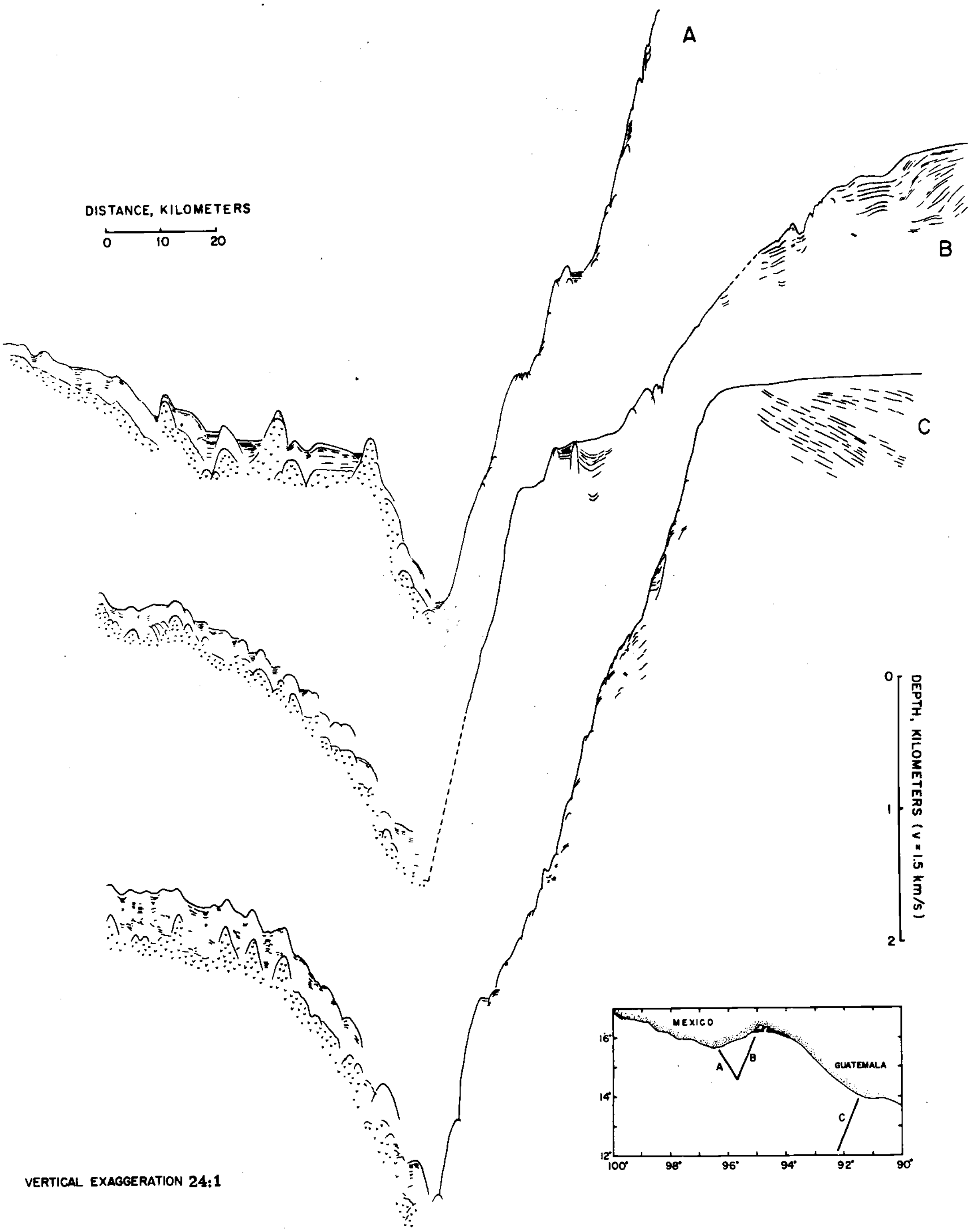

Figure 4. Seismic reflection profiles across the Middle America Trench.

crust just seaward of the trench is apparent in all three of these profiles, but is especially pronounced in profile B which is near the intersection of the axis of the Tehuantepec Ridge and the Middle America Trench. The amount of sediment fill in the trench is indeterminate in these profiles due to poor record quality in very deep water.

In profile A there are two benches on the continental slope, only one of which is sediment filled, and no obvious continental shelf. Profile B shows the very northern end of the continental shelf typical of the region southeast of the Gulf of Tehuantepec and a relatively wide sediment filled basin about half way down the slope. The reflecting horizons under the shelf in this profile are not continuous for any great distances but appear to dip seaward, with deeper horizons dipping more steeply, which suggests tilting during deposition. Profile C, which corresponds to the Western Guatemala crustal and subcrustal cross section (Figure 7 and profile AA' of Figure 6), shows two very small benches on the lower continental slope and a wide continental shelf. Under the shelf the reflecting horizons dip landward with the deeper reflectors again dipping more steeply. This suggests uplift of the outer shelf during sediment deposition. The deepest reflectors on the landward end of this profile indicate a sediment fill of at least 1.3 km based on a sediment velocity of 2.15 km/sec, but the base of the sediment is not apparent.

Gravity Data

Most of the gravity data used in this study were obtained by the Oregon State University R/V YAQUINA during cruises in 1969, 1971 and 1973. Measurements were made in 1971 and 1973 with LaCoste-Romberg surface ship gravity meter S-42 operating on a stable table. Corrections applied at sea include low pass resistance-capacitance filtering to eliminate high frequency vertical accelerations associated with wave action and cross-coupling corrections to eliminate the effect of horizontal accelerations. The 1969 data, taken with gimbal mounted LaCoste-Romberg surface ship gravity meter S-9, had the Browne Correction and a low pass R-C filter applied at sea.

During data reduction on land, base ties were used to determine meter drift and convert relative meter readings to absolute gravity. Because of poor base ties in Puntarenas, Costa Rica, meter drift was obtained for only one cruise through the Tehuantepec Ridge area. It was found to be approximately 1 mgal during a cruise of about three weeks (M. Gemperle, personal communication). The base stations for this cruise were Balboa, Panama and San Diego, California. Application of Eötvös Corrections and subtraction of the theoretical gravity value according to the International Gravity Formula (International Association of Geodesy, 1967) yielded free-air anomalies. Final gravity values are reported at 5 minute intervals which corresponds to a spatial frequency of approximately 0.7 points per kilometer.

Satellite fixes taken at intervals of about 1.5 hours provided the primary ships position information. Gyro heading and speed log data were used as necessary between fixes, and combined with the satellite fixes provided the information necessary for Eötvös Corrections. Estimated navigational accuracies are $\pm$ 0.1 kts in ship speed, $\pm 1^{\circ}$ in heading and $\pm$ 0.2 km in position (M. Gemperle, personal communication).

An analysis of 26 trackline crossing differences indicates an RMS uncertainty of 5.8 mgal for gravity stations in the Tehuantepec Ridge area. Unfortunately, of the 26 trackline crossings analyzed, 23 involve the 1971 cruise during which the gravity meter was not working properly. A crosscorrelation method was applied to these data (LaCoste, 1973) to reduce the errors, but the gravity profiles still show very short wavelength perturbations and consequently have been further smoothed for modeling purposes.

Free-Air Anomaly Map

The largest and hence most apparent feature of the free-air gravity anomaly map of this region (Figure 5) is the gravity low associated with the Middle America Trench. This continuous anomaly is almost exactly centered over the topographic expression of the trench, and like the trench topography, changes character upon intersection with the Tehuantepec Ridge near 15°N 95.5°W. To the

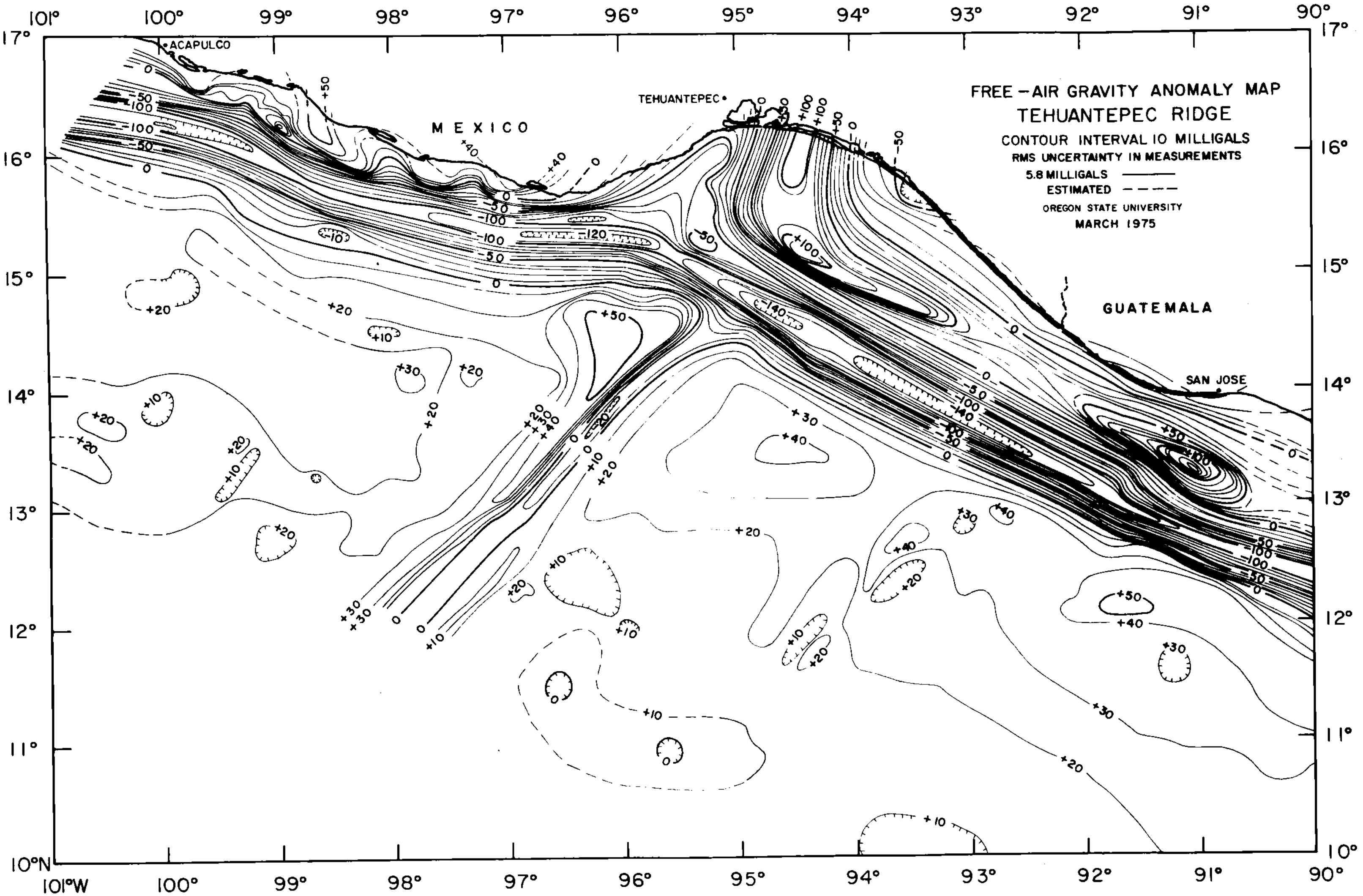

Figure 5. Free-air anomaly map of the Tehuantepec Ridge area.

northwest of the Tehuantepec Ridge the negative anomaly is relatively wide and somewhat lower in amplitude, reaching a maximum value of about -126 mgal near 15.5°N 96°W. Southeast of the ridge-trench intersection the trench anomaly is narrower, has a higher gradient and shows a maximum value of approximately -149 mgal near 14°N 93.5°W.

On the wide continental shelf to the southeast of the Gulf of Tehuantepec there is a gravity high reaching a maximum amplitude of approximately +148 mgal near 13°N 91°W. This anomaly, oriented N30°W parallels the coast of Guatemala and Southern Mexico to the Gulf of Tehuantepec where it turns abruptly inland making an almost right angle bend. Instead of being continuous along the continental shelf, the anomaly consists of at least two lobes, one off the coast of Guatemala and one off the coast of Mexico. These two lobes, both having amplitudes in excess of +100 mgal are separated by a relative gravity low of +30 mgal. This indicates that if the excess mass causing this feature was originally one continuous block, it has in some manner been deformed and separated. Alternatively, however, the lobes of this gravity high could be caused by two independent mass excesses such as high density rocks buried in a sedimentary sequence or igneous intrusions similar to those found on the adjacent continent. The amplitude and wavelength of this anomaly indicate that the source mass must be at a relatively shallow depth and that the density contrast between this mass and the surrounding material must be high. Also, this anomaly, unlike the adjacent trench anomaly, is completely independent of topography (see bathymetric map, Fig. 1) and hence must be caused entirely by a subsurface structure.

Northwest of the Gulf of Tehuantepec the continental shelf is very narrow and the gravity anomalies over the shelf are not nearly as large in areal extent or as continuous as those on the shelf to the southeast. The one notable gravity high, near 16.5°N 98.5°W, has a maximum amplitude of about +59 mgal, and is apparently associated with the topographically high Tartar Shoal, reported by Fisher (1961). A small gravity low near 15.5°N 96.3°W is associated with a perched basin evident on the seismic reflection line presented in Figure 4A.

The Tehuantepec Ridge itself is characterized by very marked positive and negative anomalies which parallel the topographic expression of the ridge. The positive anomaly appears to overlie the topographic depression southeast of the ridge. This anomaly pair shows a greater difference in amplitude near the Middle America Trench, ranging from +50 mgal to -20 mgal, whereas over the portion of the ridge more distant from the trench amplitudes of +30 mgal to -5 mgal are typical. This effect is explainable as a result of the warping of the Tehuantepec Ridge caused by subduction into the Middle America Trench.

In the Guatemala Basin just seaward of the Middle America Trench the gravity anomalies are typical of the outer gravity high discussed by Watts and Talwani (1974), and reach a maximum amplitude of +54 mgal near 12^{o}N 92^{o}W. To the northwest of the Tehuantepec Ridge and just seaward of the trench the anomaly pattern is similar but of a significantly lower amplitude and longer wavelength, exceeding +30 mgal in one isolated area. The outer gravity high has been interpreted as a consequence of lithospheric flexure caused by subduction (Watts and Talwani, 1974) which suggests that the subduction northwest of the Tehuantepec Ridge is significantly different than the subduction taking place southeast of the ridge. To the southeast of the ridge the short wavelength and high amplitude of the outer gravity high plus the relatively more negative trench anomalies indicate that the lithosphere is both being pushed higher seaward of the trench and forced lower under the trench than the lithosphere northwest of the ridge. Hence the Tehuantepec Ridge marks the boundary between two subduction provinces. This observation is further substantiated by Molnar and Sykes (1969) in their investigation of the Benioff Zone associated with the Middle America Trench. They noted that the dipping seismic zone south of the Gulf of Tehuantepec is significantly longer, measured down dip, than the corresponding zone to the north, and that the slip vectors for earthquakes in these two provinces are slightly different.

Onshore in Guatemala the gravity anomalies decrease to at least -40 mgal and possibly less, indicative of a sedimentary basin. A simple calculation assuming infinite horizontal layers, a 40 mgal gravity anomaly and a density contrast of 0.7 g/cm^3 between the sediments and the underlying rocks suggests a sediment thickness of 1.5 km. Assuming a 0.4 g/cm^3 density contrast suggests a sediment thickness of about 2.5 km. Topographically the area adjacent to the coast consists of a coastal plain about 50 km wide between the ocean and a high volcanic range. Surface geology indicates the exposed rocks are primarily Quaternary continental sediments (King _et_ _al_., 1969), which is consistent with a suggested sedimentary basin in the area of the gravity minimum.

In the Guatemala Basin near 12°N 94°W there is a series of gravity highs and lows trending approximately N45°E. These anomalies are superimposed on the outer gravity high and cause short wavelength perturbations in the anomaly contours. These anomalies coincide with a series of linear ridges and depressions evident on the bathymetric chart of the region (USNOO, 1971; Figure 1).

The average free-air anomaly in this region is positive. The only area which approaches a zero anomaly is near 11°N 96°W, but data here are sparse and the contours are somewhat questionable. This absence of areas with near zero free-air anomalies indicates that this region is not, at least locally, in isostatic equilibrium. This disequilibrium is likely due to active and relatively rapid tectonism in the vicinity of the Middle America Trench.

Crustal and Subcrustal Cross Sections

Figure 6 shows the locations of three crustal and subcrustal cross sections and the locations of the constraining seismic refraction stations. Orientation of the profiles normal to linear features allows computation of free-air gravity anomalies of two-dimensional structures by the method of Talwani et al. (1959). Profile AA' is oriented normal to the Middle America Trench and continental shelf off Western Guatemala, profile BB' is oriented normal to the trench and continental shelf off Southwestern Mexico, and profile CC' is normal to the Tehuantepec Ridge. The crustal models are constructed assuming no lateral density changes below 50 km.

The 12 kHz echo sounder records taken simultaneously with the gravity data provided information on water depths along a profile and seismic reflection records provided estimates of sediment thickness based on an assumed sediment velocity of 2.15 km/sec. Figure 3 is a line drawing of the reflection record corresponding to cross section CC' and Figure 4C corresponds to cross section AA'. Land gravity stations obtained from the Department of Defense Gravity Library constrain the crustal and subcrustal cross sections extending onto the Central American continent. Operational Navigation Charts prepared

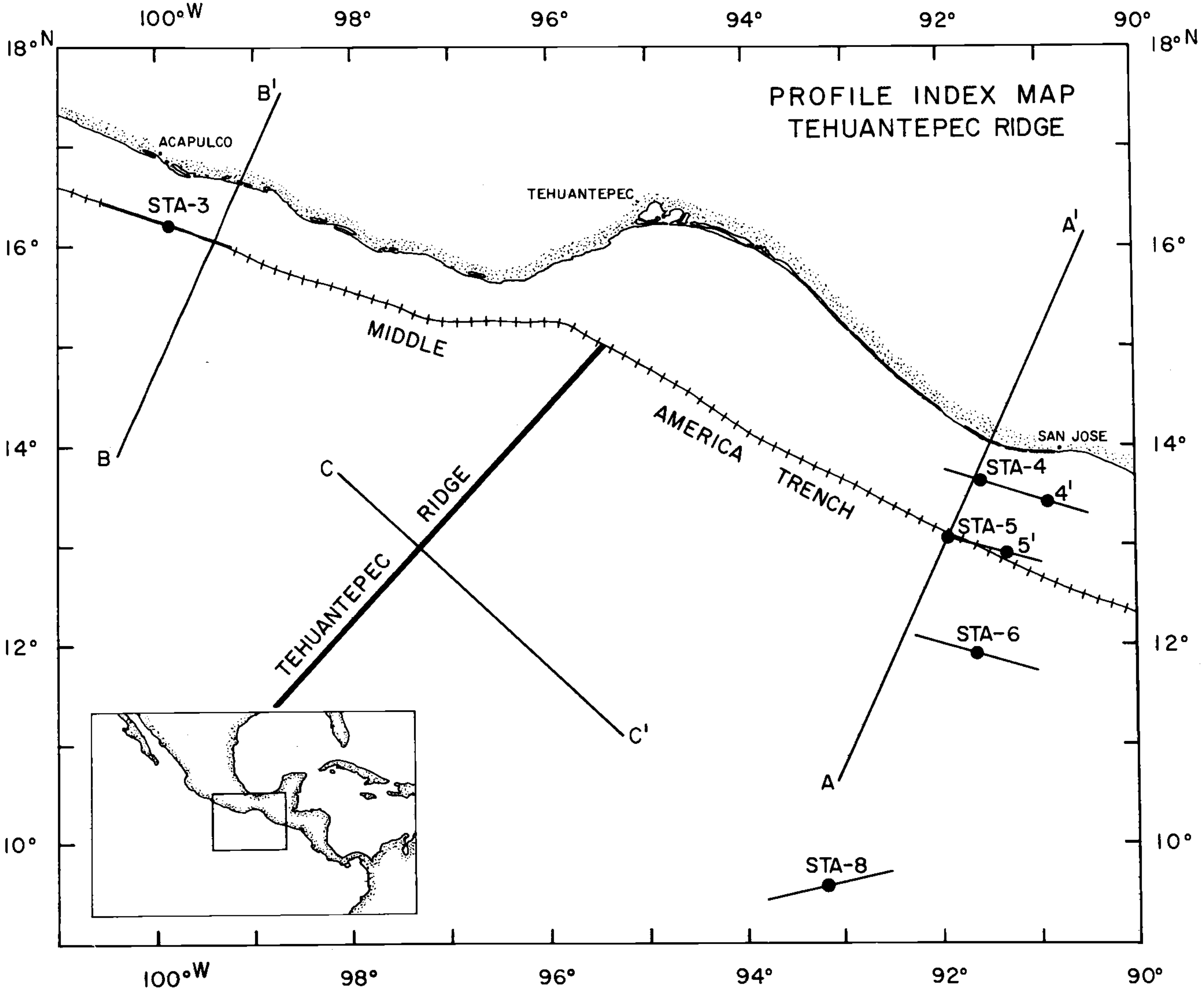

Figure 6. Profile and seismic refraction index map, Tehuantepec Ridge area.

and published by the Defense Mapping Agency Aerospace Center provided elevations on land. Additional elevation data were obtained from the known elevations of the land gravity stations.

A standard section on the seaward ends of the two trench profiles makes the sections all directly comparable. The choice of a standard section is arbitrary, but it does include consideration of age of the crust, water depth, geographic position and other geological and geophysical factors. A recent investigation of seismic refraction stations in the Eastern Equatorial Pacific (Barday, 1974) resulted in the derivation of a standard oceanic section for application in the Panama Basin. Due to the proximity of this region to the Tehuantepec Ridge and the thoroughness of the investigation, the Barday (1974) standard section is applied to the seaward ends of the two profiles normal to the Central American continental margin.

One change is made to this standard section which is not specifically shown on the cross sections. The density of the transition layer (layer 2) is changed from 2.60 g/cm^3 to 2.70 g/cm^3 on the basis of seismic refraction results. Layer velocities indicated by seismic refraction and the wide scatter in the velocities encountered in this layer (Shor _et_ _al_., 1970) make this change reasonable.

Refraction stations STA-3 (see Figure 6 and Table 1) indicates a transition layer 2.31 km thick with a seismic velocity of 5.25 km/sec (Shor and Fisher, 1961) which corresponds to a density between about

Table 1. Seismic Velocities and Layer Thicknesses.

Station	Water		Sediment		Basement		Crust		Mantle	Σh
	h_0	v_0	h_1	v_1	h_2	v_2	h_3	v_3	v_4	
3	5.14	1.54	0.39	2.15	2.31	5.25	3.93	6.82	8.24	11.77
4	0.12	1.50	0.50	1.71	3.84	4.40	6.53	6.88	8.18	17.59
			0.74	2.41	4.03	5.83				
			1.83	3.25						
4'	0.12	1.50	0.58	1.71	4.81	4.40	4.33	6.88	8.18	15.34
			1.75	2.41	2.61	5.83				
			1.14	3.25						
5	6.18	1.54	1.00	2.15			9.84	6.69	8.04	17.02
5'	6.02	1.54	1.20	2.15			5.36	6.69	8.04	12.58
6	3.62	1.53	0.80	2.15			3.69	6.76	7.76	8.11
8	3.74	1.50	0.11	2.15	1.45	4.32	4.13	6.84	8.22	9.43

h_i = thickness in km

v_i = velocity in km/sec

Stations 3, 4, 4', 5, 5' and 6 from Shor and Fisher (1961).

Station 8 from Shor <u>et al</u>. (1969).

4-4' and 5-5' indicate reversed lines.

2.40 g/cm^3 and 2.85 g/cm^3 (Ludwig, Nafe and Drake, 1970, Fig. 11). If a density of 2.60 g/cm^3 is used and the depths to layers as determined by seismic refraction are strictly adhered to, the computed gravity over the trench is 10 mgal low. Changing the density of the transition layer to 2.70 g/cm^3 yields the correct gravity value.

The lower continental crust is assumed to be composed of two layers with densities of 2.75 and 3.00 g/cm^3, and the upper crustal densities are chosen consistent with rock types indicated by surface geology. North of the Isthmus of Tehuantepec (i.e., section BB') the surface rocks are primarily Paleozoic metamorphics whereas south of the isthmus (i.e., section AA') the surface rocks are primarily Cenozoic volcanics (King *et al.*, 1969). Hence the upper crustal layer in section AA' (Figure 7) has a density of 2.60 g/cm^3 and the upper crustal layer in section BB' (Figure 8) has a density of 2.65 g/cm^3.

Construction of a model combines the constraints imposed by water depth, sediment thickness, land elevations and seismic refraction data, and iterative adjustments to layer boundaries are made until the computed gravity agrees with the observed free-air anomaly and computed magnetic intensity agrees with the observed magnetic anomaly.

Western Guatemala Crustal and Subcrustal Cross Section

The Western Guatemala crustal and subcrustal cross section (Figure 7 and profile AA' of Figure 6) crosses the Middle America Trench near 13°N 92°W, passes about 70 km northwest of Guatemala City and terminates in central Guatemala near 16°N 90.5°W. The seaward end of this profile extends through the southeastern edge of the Guatemala Basin to a terminus near 10.5°N 93.5°W. The sea floor on the southwestern end of this profile is at a water depth of approximately 3.7 to 3.8 km increasing to about 6.2 km depth in the Middle America Trench. Land elevations reach a maximum of about 3.0 km above sea level approximately 70 km from the coast.

The observed free-air gravity anomaly is near +10 mgal on the seaward end of the profile, increasing to about +35 mgal just seaward of the trench. There is no regional rise in topography associated with this outer gravity high as has been noted near the Aleutian, Kuril, Japan and northern Bonin Trenches (Watts and Talwani, 1975). Over the Middle America Trench there is a broad gravity low ranging to about -130 mgal which is caused by increased water depth and a thickening of the oceanic layer. Unlike many gravity profiles across active trenches (e.g., Watts and Talwani, 1974; Goebel, 1974) this negative anomaly is not shifted landward of the trench axis but is almost exactly centered on the axis. Landward of the trench over the

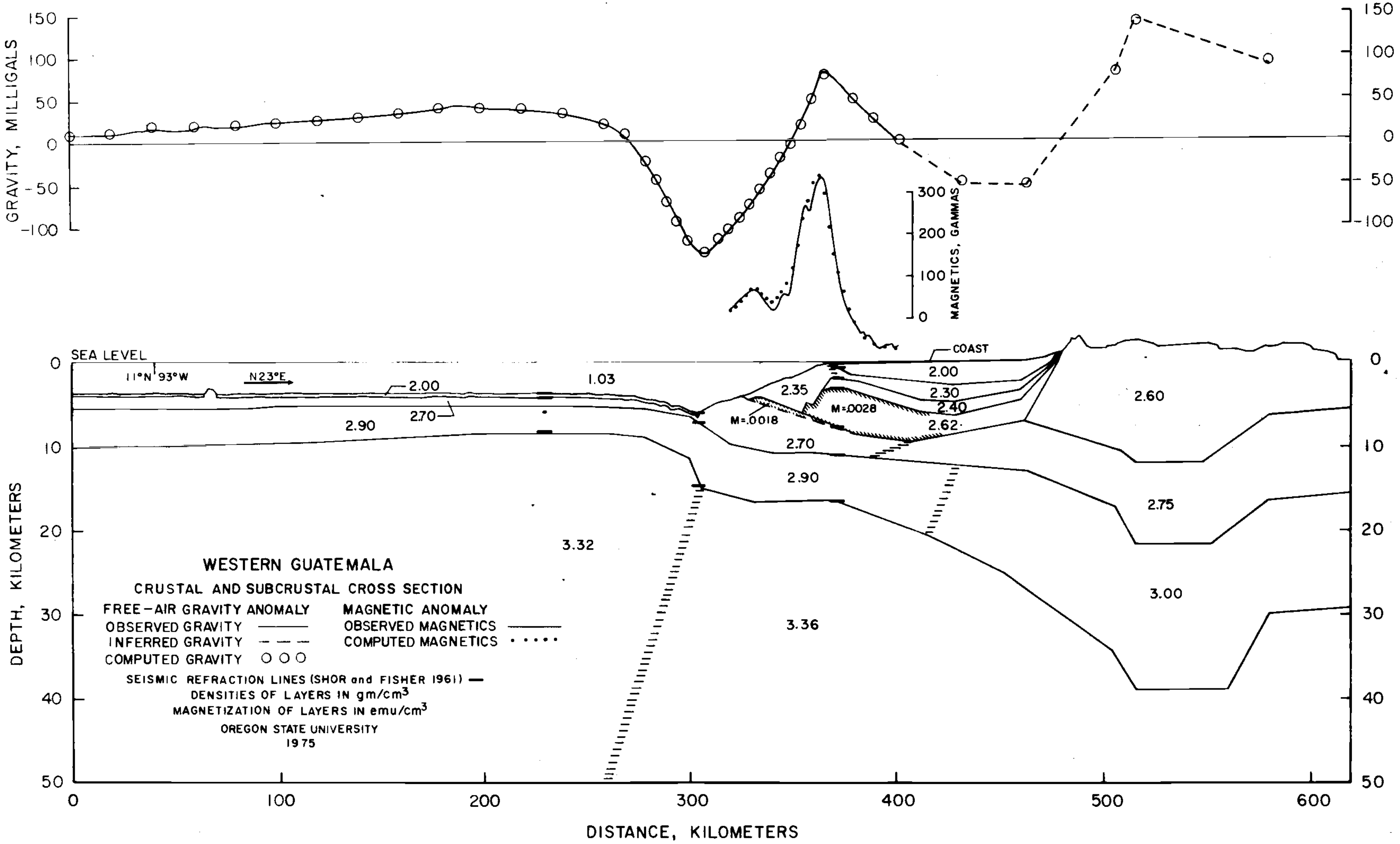

Figure 7. Western Guatemala crustal and subcrustal cross section.

outer continental shelf there is a gravity high of about +80 mgal caused primarily by a relatively shallow 2.62 g/cm^3 layer, and a broad low centered about 30 km inland from the coast which is caused by a large low density basin.

Observed magnetic anomalies along the Western Guatemala profile have amplitudes of less than 100 gammas except in two isolated places. One of these is located about 60 km seaward of the trench. It is not shown in Figure 7 as no attempt was made to model the source of the magnetic anomalies in the Guatemala Basin. The other, located over the seaward edge of the continental shelf, has a maximum amplitude of +335 gammas. Because of the diminution of the oceanic anomalies seaward of the trench this shelf anomaly is assumed due to induced magnetization and consequently the source is modeled by the method of Talwani and Heirtzler (1964).

Three seismic refraction stations constrain the depths to layers and the observed seismic velocities (Shor and Fisher, 1961) yield layer densities via the empirical relationship of Ludwig, Nafe and Drake (1970).

Between the seaward end of the profile and the trench, the Moho shoals from 10.1 km depth to about 8.4 km depth causing the outer gravity high. Directly under the trench the Moho dips at an angle of about 30° to a depth of approximately 15 km before leveling off under the continental shelf. In order to agree with depth to Moho under the trench as indicated by seismic refraction a high density mantle is included beneath and landward of the trench. Thinning the crust under active trenches has frequently been necessary to satisfy observed gravity in structural sections such as this. Alternatively, lateral density changes in both the crust and mantle have been used (e.g., Dehlinger et al., 1970; Solomon and Biehler, 1969) and Grow and Bowin (1975) suggest that such variations may be indicative of phase changes in the downgoing slab. In this case a discontinuity of 0.04 g/cm^3 as shown in Figure 7 is the minimum necessary to satisfy both the gravity and seismic refraction. Refraction data are consistent with this interpretation because the seismic velocity of the mantle increases from 7.76 km/sec seaward of the trench, to 8.04 km/sec in the trench, to 8.18 km/sec under the continental shelf (Shor and Fisher, 1961).

The continental shelf structure in the Western Guatemala crustal and subcrustal cross section includes a large sedimentary basin which extends from the outer shelf to the foot of the volcanic range in Guatemala, and reaches a maximum depth of just over 6 km landward of the coast. This type of structure is consistent with seismic reflection data (Ross and Shor, 1965), seismic refraction (Shor and Fisher, 1961) and land geology (King et al., 1969). The basin is underlain by a magnetic layer of density 2.62 g/cm^3 which is considered the primary layer forming the magnetic anomaly associated with the outer shelf. A magnetic anomaly source is also included in a portion of the 2.70 g/cm^3 layer to create an observed magnetic peak just seaward of the main magnetic anomaly.

The continental root associated with this portion of Central America extends to a depth of about 39 km in the model. This figure agrees reasonably well with the closest seismic refraction on land at 24.03°N 104.15°W which indicates a crustal thickness of 43.4 km (McConnell and McTaggart-Cowan, 1963). Another study involving analysis of surface waves of earthquakes off the coast of Chiapas, Mexico indicates a crustal thickness in Central Mexico of about 30 km (Fix, 1974).

Southwestern Mexico Crustal and Subcrustal Cross Section

The Southwestern Mexico crustal and subcrustal cross section (Figure 8 and profile BB' of Figure 6) crosses the Middle America Trench near 16°N 99.4°W, passes about 70 km southeast of Acapulco and terminates in Mexico near 17.5°N 98.8°W. The seaward end of this profile terminates near 14°N 100.4°W. Water depth on the seaward end of this model is near 3.5 km where the sea floor is relatively flat and increases to approximately 5.2 km in the Middle America Trench. Land elevations reach a maximum of about 1.5 km above sea level approximately 80 km from the coast.

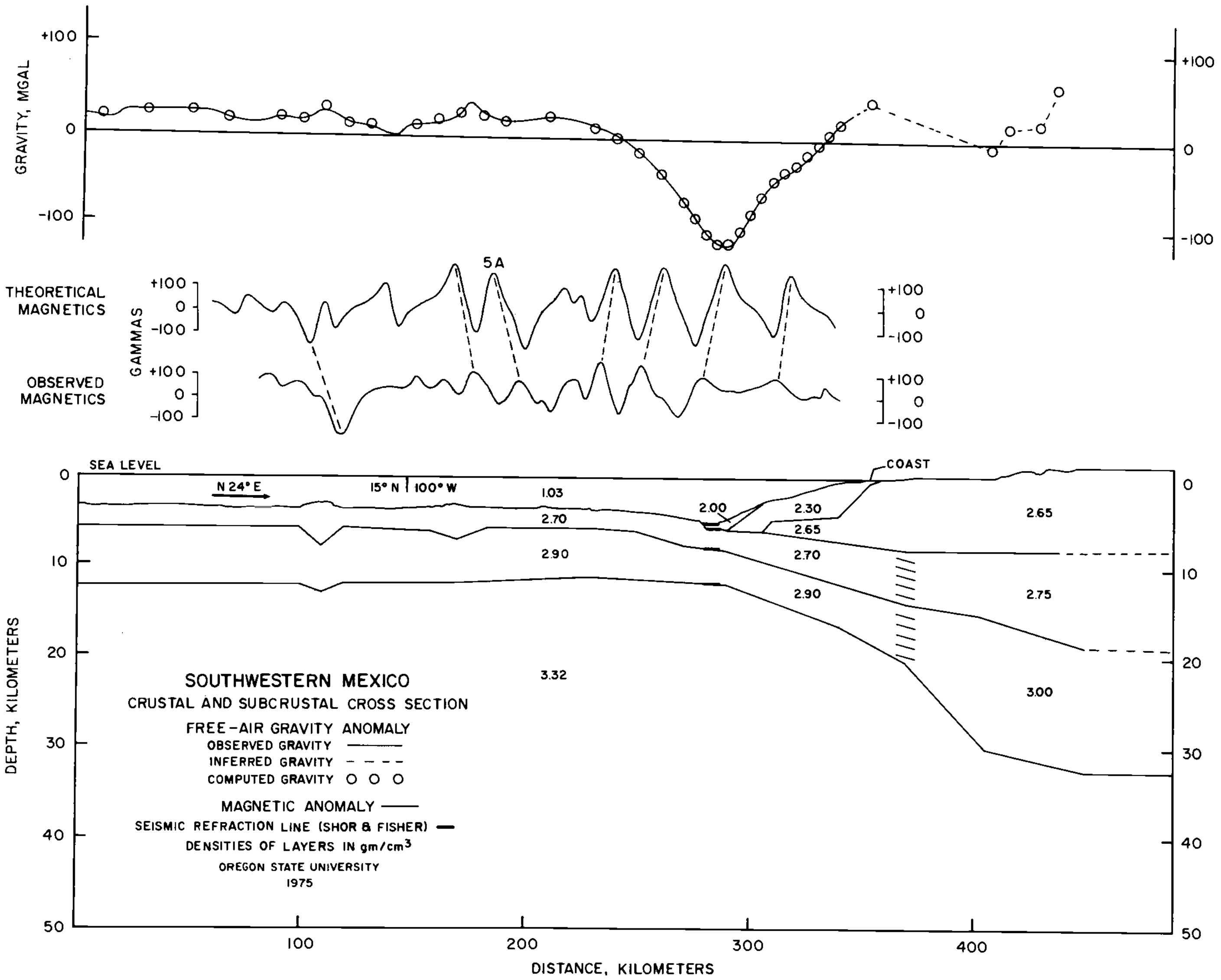

Figure 8. Southwestern Mexico crustal and subcrustal cross section.

The observed free-air gravity anomaly is near +20 mgal on the seaward end of the Southwestern Mexico cross section, and there is no apparent outer gravity high. The gravity low associated with the Middle America Trench reaches a maximum negative amplitude of about -120 mgal almost directly over the topographic low of the trench. A gravity high of about +40 mgal occurs just landward of the coast and a broad gravity low occurs just seaward of the mountains.

Observed and theoretical magnetic anomalies along the Southwestern Mexico profile are included in Figure 8. Theoretical anomalies are generated assuming remnant magnetization in the upper kilometer of the oceanic crust and a spreading axis oriented N20°W. The East Pacific Rise in this region is oriented almost north-south, but the magnetic anomalies in the basin to the east are not parallel to the ridge (Lewis et al., 1975; W. Lynn, personal communication), and the N20°W orientation noted above is intended to account for this fanning of anomalies. The time scale used to generate theoretical anomalies is that of Blakely (1974).

The only seismic refraction station on this profile indicates a transition layer thickness of about 2.3 km under the trench (Shor and Fisher, 1961; Table 1). This thickness is somewhat greater than the Pacific Basin average of 1.21 km (Shor et al., 1970) but it is reasonable and is therefore used, except for short wavelength variations, for the entire profile.

At the seaward end of this profile the depth to Moho is approximately 12 km. The crust thins to about 11 km seaward of the trench and thickens smoothly to about 33 km under the continent. This is in good agreement with recent seismic refraction observations reported by Helsley *et al.* (1975). The continental shelf structure in this profile includes only two blocks in great contrast to the complex shelf structure in the Western Guatemala structural profile.

There is no sediment indicated on the seaward end of this crustal and subcrustal cross section because no seismic reflection information was available. However, a nearby trackline, which includes reflection data, indicates a sediment cover of about 100 meters which could have been included in this model as a uniform cover. The inclusion of a uniform cover of 2.00 g/cm^3 density material 100 meters thick would decrease the computed gravity by about 2.5 mgal and decrease the depth of the Moho by less than 0.2 km. This relatively small effect coupled with the inability to distribute the sediment properly makes the exclusion of this layer a reasonable approximation.

Tehuantepec Ridge Crustal and Subcrustal Cross Section

The Tehuantepec Ridge crustal and subcrustal cross section (Figure 9 and profile CC' of Figure 6) crosses the Tehuantepec Ridge near 13°N 97.2°W, terminating on its southern end in the Guatemala

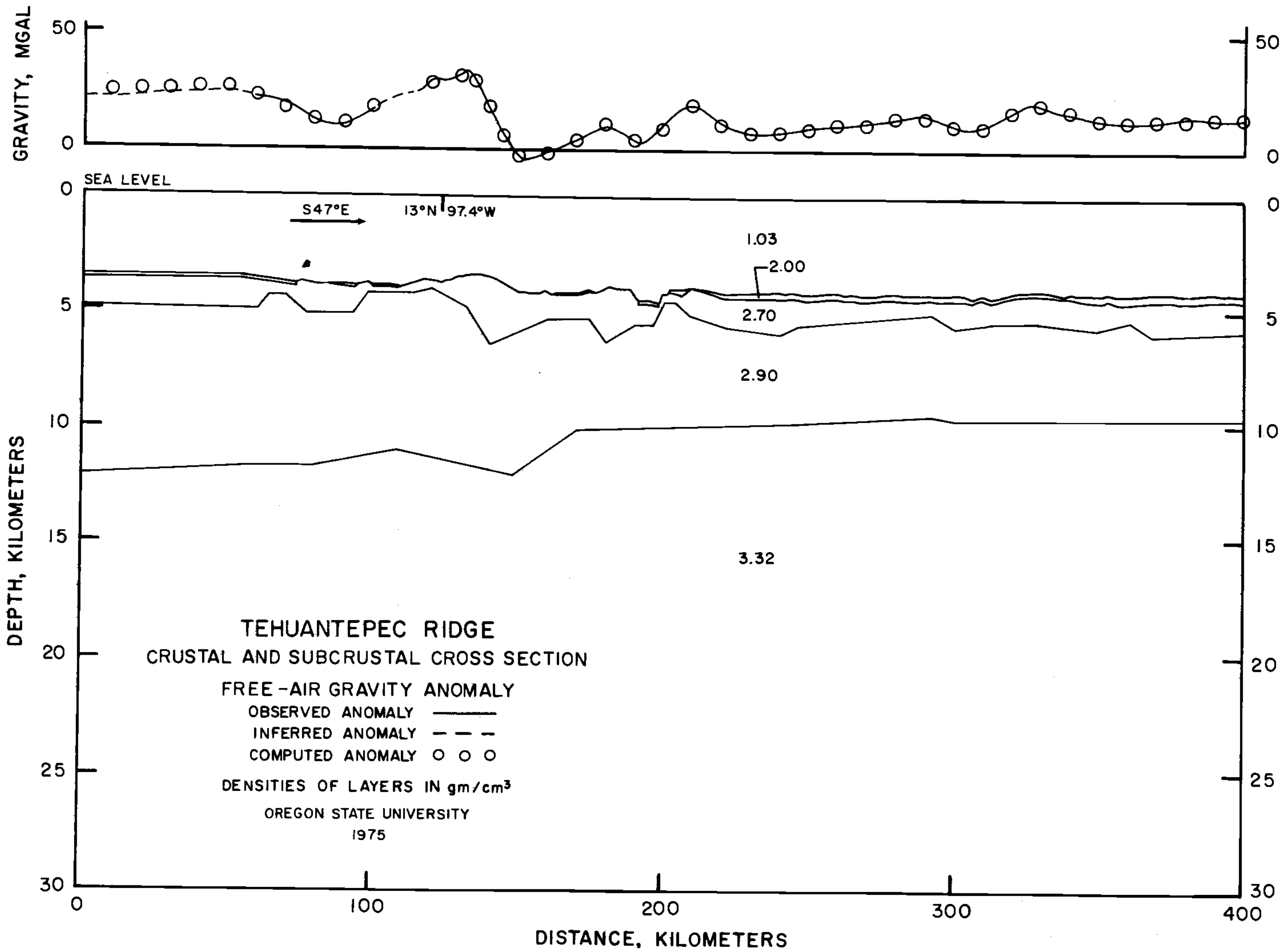

Figure 9. Tehuantepec Ridge crustal and subcrustal cross section.

Basin near 11°N 95.2°W and on its northern end near 13.8°N 98.2°W. In the Guatemala Basin (right side of Figure 9) the sea floor is generally at a depth of 4.0-4.2 km with local deviations, and northwest of the ridge the sea floor is at a depth of about 3.5 km. On the extreme left side of Figure 9 water depth is estimated from the USNOO Bathymetric Atlas of the Northeastern Pacific Ocean (1971) and the free-air gravity anomaly is estimated from Figure 4. Traversing the ridge from northwest to southeast one encounters a broad depression reaching a depth of about 3.8 km (2078 fm), a relatively subdued ridge shoaling to about 3.4 km (1860 fm), a narrower depression reaching a depth of approximately 4.2 km (2297 fm), a graben-like structure flanked on both sides by small ridges and reaching a maximum depth of about 4.5 km (2450 fm) and then the relatively smooth sea floor of the Guatemala Basin.

The observed free-air gravity anomaly northwest of the ridge decreases from about +23 mgal to about +10 mgal over the northwestern depression. The linear positive and negative anomalies typical of the Tehuantepec Ridge range approximately from +35 mgal to -5 mgal. Southeast of the ridge there are a number of short wavelength free-air anomalies superimposed on a long wavelength anomaly which increases to about +15 mgal in the central Guatemala Basin.

The CH-8 seismic refraction station of Shor et al. (1970) was used off the southeast end of the Tehuantepec Ridge crustal and subcrustal cross section but is not shown in Figure 9. The location of station 8 is shown in Figure 6. Only the depths to layers are applied to the profile because densities are kept consistent with the Western Guatemala and Southwestern Mexico crustal and subcrustal cross sections. Agreement with layer thicknesses as indicated in the Western Guatemala profile is good.

It is apparent from this crustal and subcrustal cross section that the Tehuantepec Ridge is a boundary between two crustal provinces. Northwest of the ridge the crust has a thickness of about 12 km whereas southeast of the ridge the crustal thickness is about 9.5 km. There is some short wavelength warping of the Moho directly under the Tehuantepec Ridge but there is no apparent crustal root as is found under the Cocos and Nazca Ridges (Barday, 1974; Whitsett, 1975) and the Rivera Fracture Zone (Gumma, 1974). The long wavelength change in observed gravity noted above is manifested in this section as a gentle slope in the Moho from just southeast of the ridge to the extreme southeastern end of the profile.

The transition layer in this structural model generally has a thickness of about 1.5 km but there are some extreme variations from this figure. Under the southeast flank of the Tehuantepec Ridge the transition layer thickens to about 2.7 km and just to the northwest it thins to about 0.3 km. The extreme variability of the transition layer thickness near the Tehuantepec Ridge suggests tectonic modification of the structure.

CONCLUSIONS

Continental Shelf Structure

The continental shelf off Western Guatemala as detailed in Figure 7 includes a large sedimentary basin which is postulated here to contain continental sediments which are compacted with depth to a density of 2.40 g/cm^3 at about 4 km depth. The upper continental slope, with a density of 2.35 g/cm^3 can be interpreted as slumped continental sediments and possibly some accreted trench sediments at an intermediate stage of compaction. Except for a possible veneer of sediment, the lower slope has material of 2.70 g/cm^3 density exposed at the surface which is difficult to account for in the context of the trench slope model of Seely et al. (1974). However, in the Peru Trench the oceanic basement layer is apparently involved in the imbricate thrusting phenomenon (Prince and Kulm, 1975) which suggests the 2.70 g/cm^3 density block in the Western Guatemala lower slope may be explained as a melange of sediments and oceanic basement. The sedimentary basin forming the upper part of this continental shelf is underlain by a layer of 2.62 g/cm^3 density which is assumed to have an induced magnetization. This layer is interpreted here as being continuous with or at least genetically similar to the Nicoya Complex of Costa Rica. Analysis of exposed rock types on the

Nicoya Peninsula (Dengo, 1962; Table 1) using densities listed by Woollard (1962) indicates an expected overall density of about 2.6 g/cm^3 for the Nicoya Complex (see Table 2) which is in good agreement with the 2.62 g/cm^3 density obtained in the gravity model.

The continental shelf off Southwestern Mexico as shown in Figure 8 is composed primarily of one large block with a density of 2.30 g/cm^3. This block probably consists of continental sediments in its upper part and accreted oceanic sediments in the lower part. The relatively large 2.00 g/cm^3 density block in and just landward of the trench bottom indicates a large amount of trench fill which is not significantly compacted in the initial stages of imbricate thrusting. The 2.65 g/cm^3 density nose in the lower shelf can be interpreted as a portion of the continental crust or an earlier stage of the same process which formed the 2.62 g/cm^3 block in the Western Guatemala shelf structure.

The primary source mass of the positive gravity anomaly on the continental shelf southeast of the Gulf of Tehuantepec (see Figure 5) is apparently the 2.62 g/cm^3 density layer shown in the Western Guatemala crustal and subcrustal cross section. It has already been postulated that this layer represents the northern extension of the Nicoya Complex, hence it is apparent from Figure 5 that this rock sequence underlies the shelf in the Gulf of Tehuantepec and makes an abrupt bend into the Central American continent. The amplitudes of

Table 2. Density of the Nicoya Complex.

Layer Description	T	% T	D	C
Basalt agglomerate	100	16	2.5	0.40
Coarse, unsorted graywacke	5	1	2.3	0.02
Basalt, agglomerate w/interbeds of chert and jasper	50	8	2.5	0.20
Basalt agglomerate w/interstitial jasper	25	4	2.5	0.10
Pillow basalt w/crystalline limestone and interstitial jasper	175	28	2.5	0.70
Siliceous limestone, finely crystalline	30	5	2.7	0.14
Conglomerate w/graywacke, diabase basalt and jasper	150	24	2.7	0.65
Conglomerate w/intrusive diabase	86	14	2.7	0.38
	(base not exposed)			
Totals	621	100		2.59

T = thickness of layer in meters; % T = percent of total thickness;
D = density of layer in g/cm^3; C = contribution to total density.

Layer descriptions and thicknesses adapted from Dengo (1962, table 1).

Densities from Woollard (1962, part 3, table 2).

both the gravity and magnetic anomalies caused by this layer should be indicative of the depth to the top of the layer. In the region between the two lobes of the gravity high (see Figure 5) the magnetic anomaly has an amplitude of about 100 gammas and nearer the Gulf of Tehuantepec where the gravity anomaly is in excess of +100 mgal the magnetic anomaly has an amplitude of approximately 260 gammas. The two lobes of this positive gravity anomaly can thus be interpreted as representing two separate pieces of Nicoya-type rock sequence or two relatively shallow pieces separated by a deeper portion of the same material.

On the basis of volcanological and seismological evidence the Central American-Mexican arc can be broken into 14 segments (Carr _et_ _al_., 1974) which apparently represent semi-independent tectonic provinces. Both of the lobes of the continental shelf gravity high discussed above lie between proposed boundaries of these segments. This suggests a tectonic mechanism which could have either separated the pieces of Nicoya-type complex if they were once joined or formed them separately.

The bending of this gravity anomaly into the continent in the Gulf of Tehuantepec implies, by the present interpretation, that the Nicoya-type rock sequence does the same. Whether the source mass was moved to this orientation or formed in its present position or how far inland the anomalous mass continues cannot be determined from the available data. If this portion of the complex had its origin along the present Middle America Trench as the remainder of it appears to have, it may have been moved to its present orientation as a result of interaction with the subduction of the Tehuantepec Ridge. However, such a large scale horizontal movement of a coherent body is difficult to imagine. Alternatively, the source mass for this anomaly may have been formed in its present location. This implies that imbricate thrusting once took place across at least part of what is now the Isthmus of Tehuantepec with an axis of compression oriented northwest-southeast, but geological evidence for such a process is lacking.

Tehuantepec Ridge Structure and Origin

When the Tehuantepec Ridge was discovered it was immediately assumed to be a fracture zone because of its topography, which resembled that of the other known fracture zones of the Northeast Pacific, and its apparent continuity with the Clipperton Fracture Zone (Menard and Fisher, 1958). Since that time, however, it has not been clear that the Tehuantepec Ridge is a fracture zone, and consequently a number of alternative theories have been suggested. On the basis of the orientations of the Tehuantepec, Cocos and Nazca Ridges it has been suggested that the Tehuantepec Ridge may be a hot spot trace (Herron, 1972). Truchan and Larson (1973) postulate that the ridge might be a hinge fault, similar to that at the northern end of the Tonga Trench, accommodating the difference between North American-Cocos relative motion and Caribbean-Cocos relative motion. The Tehuantepec Ridge crustal and subcrustal cross section (Figure 9) suggests the ridge is the surface expression of a fracture zone because it separates a region of about 9.5 km thick crust from a region of about 12 km thick crust.

Differences in water depth, sediment thickness and magnetic character all indicate the crust in the Guatemala Basin is older than the crust on the north side of the Tehuantepec Ridge. A simple calculation using the depth vs. distance from the ridge crest relation of Sclater and Francheteau (1970) and the Cocos-Pacific pole location and rate of rotation (Minster et al., 1974) suggests a crustal age of about 10 my for the northwest end of the Tehuantepec Ridge profile (Figure 9) and an age of about 20 my for the southeast end of the profile. The 10 my age for the crust northwest of the ridge is consistent with the observed magnetic anomalies along the Southwestern Mexico crustal and subcrustal cross section (Figure 8). As previously noted, the total sediment cover is approximately 100 meters northwest of the Tehuantepec Ridge and approximately 300 meters southeast of the ridge. Assuming the sedimentation history was similar for the two regions it can again be concluded there is an age discontinuity across the Tehuantepec Ridge. If steady state sedimentation is assumed, the crust in the Guatemala Basin can be dated at about 30 my on the basis of a known age of 10 my for the crust to the northwest. Just south of the Guatemala Basin magnetic anomalies 12 and 13 have been tentatively identified (Herron, 1972), and extrapolation of these anomalies into the basin indicates an age of roughly 35 my for the southeastern end of the Tehuantepec Ridge structural profile. Hence these three very approximate methods suggest an age difference of 10-25 my across the Tehuantepec Ridge.

Because of its apparent aseismicity and an orientation oblique to present plate motions the Tehuantepec Ridge can be interpreted as a relic fracture zone. However, regardless of its origin it still may be a zone of relative weakness in the crust of the Cocos Plate. Because it is located at a boundary between two significantly different subduction provinces, it may be seismically active. Molnar and Sykes (1969), on the basis of one earthquake in 1933 which apparently occurred on the Tehuantepec Ridge near 12.73°N 97.80°W, propose that it is a site of very low but occasional seismic activity. These observations suggest the Tehuantepec Ridge may indeed be seismically active but with earthquakes whose magnitudes are too low to be recognized with land based seismic stations.

BIBLIOGRAPHY

Agassiz, A. 1906. General report of the expedition (Albatross Expedition 1904-1905). Museum of Comparative Zoology Memoirs, v. 33.

Anderson, R.N. 1974. Cenozoic motion of the Cocos Plate relative to the asthenosphere and cold spots. Geological Society of America Bulletin 85:175-180.

Barday, R.J. 1974. Structure of the Panama Basin from marine gravity data. M.S. thesis. Corvallis, Oregon State University. 99 p.

Blakely, R.J. 1974. Geomagnetic reversals and crustal spreading rates during the Miocene. Journal of Geophysical Research 79:2979-2985.

Bowles, F.A., R.N. Jack and I.S.E. Carmichael. 1973. Investigation of deep-sea volcanic ash layers from equatorial Pacific cores. Geological Society of America Bulletin 84:2371-2388.

Carr, M.J., R.E. Stoiber and C.L. Drake. 1974. The segmented nature of some continental margins. In: The Geology of Continental Margins. C.A. Burk and C.L. Drake, editors. p. 105-114.

Chase, T.E. 1968. Sea floor topography of the Central Eastern Pacific. U.S. Department of Interior (Commercial Fisheries) Circular 291. 33 p.

Dehlinger, P., R.W. Couch, D.A. McManus and M. Gemperle. 1970. Northwest Pacific structure. In: A.E. Maxwell (editor), The Sea. Vol. 4, Part II. New York, Wiley-Interscience. p. 133-189.

Dengo, G. 1962. Tectonic-igneous sequence in Costa Rica. In: Petrologic Studies: A Volume to Honor A.F. Buddington. A.E.J. Engel, H.L. James and B.F. Leonard, editors. Geological Society of America, publisher. p. 133-161.

Fisher, R.L. 1961. Middle America Trench: topography and structure. Geological Society of America Bulletin 72:703-720.

Fix. J.E. 1974. The crust and upper mantle of Central Mexico. Transactions, American Geophysical Union (EOS) 55:359.

Goebel, V. 1974. Modeling of the Peru-Chile Trench from wide-angle reflection profiles. M.S. thesis. Corvallis, Oregon State University. 88 p.

Grow, J.A. and C.O. Bowin. 1975. Evidence for high-density crust and mantle beneath the Chile Trench due to the descending lithosphere. Journal of Geophysical Research 80:1449-1458.

Gumma, W.H. 1974. An interpretation of the gravity and magnetic anomalies of the Rivera Fracture Zone, Eastern Pacific Ocean. M.S. thesis. Corvallis, Oregon State University. 50 p.

Heacock, J.G. and J.L. Worzel. 1955. Submarine topography west of Mexico and Central America. Geological Society of America Bulletin 66:773-776.

Heiskanen, W.A. 1939. Catalogue of isostatically reduced gravity stations. Helsinki. 139 p. (International Association of Geodesy. Isostatic Institute. Publication no. 5)

Helsley, C.E., J.B. Nation and R.B. Meyer. 1975. Seismic refraction observations in Southern Mexico. Transactions, American Geophysical Union (EOS) 56:452.

Herron, E.M. 1972. Sea-floor spreading and the Cenozoic history of the East-Central Pacific. Geological Society of America Bulletin 83:1671-1692.

International Association of Geodesy. 1967. Geodetic reference system 1967. Special Publication no. 3.

King, P.B. et al. 1969. Tectonic map of North America. Department of the Interior, U.S. Geological Survey.

LaCoste, L.J.B. 1973. Crosscorrelation method for evaluating and correcting shipboard gravity data. Geophysics 38:701-709.

Langseth, M.G., P.J. Grim and M. Ewing. 1965. Heat-flow measurements in the Eastern Pacific Ocean. Journal of Geophysical Research 70:367-380.

Lewis, B.T.R., W. Lynn and W. Snydsman. 1975. Magnetic anomaly fanning on the Northern Cocos Plate. Transactions, American Geophysical Union (EOS) 56:453.

Ludwig, W.J., J.E. Nafe and C.L. Drake. 1970. Seismic refraction. In: A.E. Maxwell (editor), The Sea. Vol. 4, Part I. New York, Wiley-Interscience. p. 53-84.

McConnel, R.K., Jr. and G.H. McTaggert-Cowen. 1963. Crustal seismic refraction profiles: A compilation. University of Toronto Institute of Earth Sciences, scientific report no. 8.

Menard, H.W. and R.L. Fisher. 1958. Clipperton Fracture Zone in the Northeastern Equatorial Pacific. Journal of Geology 66:239-253.

Minster, J.B., T.H. Jordan, P. Molnar and E. Haines. 1974. Numerical modeling of instantaneous plate tectonics. Geophysical Journal of the Royal Astronomical Society 36:541-576.

Molnar, P. and L.R. Sykes. 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geological Society of America Bulletin 80:1639-1684.

Prince, R.A. and L.D. Kulm. 1975. Crustal rupture and the initiation of imbricate thrusting in the Peru Trench. Geological Society of America Bulletin. (In press)

Ross, D.A. and G.G. Shor, Jr. 1965. Reflection profiles across the Middle America Trench. Journal of Geophysical Research 70: 5551-5572.

Sclater, J.G. and J. Francheteau. 1970. The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. Geophysical Journal of the Royal Astronomical Society 20:509-542.

Seely, D.R., P.R. Vail and G.G. Walton. 1974. Trench slope model. In: The Geology of Continental Margins. C.A. Burk and C.L. Drake, editors. p. 249-260.

Shor, G.G., Jr. and R.L. Fisher. 1961. Middle America Trench: Seismic-refraction studies. Geological Society of America Bulletin 72:721-730.

Shor, G.G., Jr., H.W. Menard and R.W. Raitt. 1970. Structure of the Pacific Basin. In: A.E. Maxwell (editor), The Sea. Vol. 4, Part II. New York, Wiley-Interscience. p. 3-27.

Solomon, S. and S. Biehler. 1969. Crustal structure from gravity anomalies in the Southwest Pacific. Journal of Geophysical Research 74:6696-6701.

Talwani, M., J.L. Worzel and M. Landisman. 1959. Rapid gravity computation for two dimensional bodies with application to the Mendocino submarine fracture zone. Journal of Geophysical Research 64:49-59.

Talwani, M. and J.R. Heirtzler. 1964. Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape. In: Computers in the Mineral Industries. Stanford University Publications. Vol. IX, no. 1, p. 464-480.

Truchan, M. and R.L. Larson. 1973. Tectonic lineaments on the Cocos Plate. Earth and Planetary Science Letters 17:426-432.

United States Naval Oceanographic Office. 1971. Bathymetric atlas of the Northeastern Pacific Ocean. N.O. Publication no. 1303.

Vacquier, V., J.G. Sclater and C.E. Corry. 1967. Studies of the thermal state of the earth. The 21st Paper: Heat flow, Eastern Pacific. Bulletin of the Earthquake Research Institute 45:375-393.

Vening Meinesz, F.A. 1948. Gravity expeditions at sea 1923-1938. Vol. 4. Publ. Neth. Geod. Comm., Delftche Vitgevers Mij, Delf, 1948.

VonHerzen, R.P. and S. Uyeda. 1963. Heat flow through the Eastern Pacific Ocean floor. Journal of Geophysical Research 68:4219-4250.

Watts, A.B. and M. Talwani. 1974. Gravity anomalies seaward of deep-sea trenches and their tectonic implications. Geophysical Journal of the Royal Astronomical Society 36:57-90.

Watts, A.B. and M. Talwani. 1975. Gravity effect of downgoing lithospheric slabs beneath island arcs. Geological Society of America Bulletin 86:1-4.

Whitcroft, H. T. 1944. The bathymetry of the Central American region, west coast of Mexico and northern Central America. American Geophysical Union Transactions, part 4, p. 606-608.

Whitsett, R. 1975. Gravity measurements and their structural implications for the continental margin of Southern Peru. Ph.D. thesis. Corvallis, Oregon State University. (In preparation)

Woollard, G. P. 1962. The relation of gravity anomalies to surface elevation, crustal structure and geology. University of Wisconsin, Department of Geology Research Report no. 62-9.

Worzel, J. L. 1965. Pendulum gravity measurements at sea 1936-1959. New York, John Wiley and Sons, Inc. 422 p.