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Title: A GEOPHYSICAL ANALYSIS OF THE OROZCO FRACTURE ZONE AND THE TECTONIC EVOLUTION OF THE NORTHERN COCOS PLATE

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In April of 1974, Oregon State University conducted a geophysical survey of the Orozco fracture zone, a left-lateral transform fault which offsets the East Pacific Rise off the coast of Mexico near 15°N, 105°W. Magnetic, gravity, bathymetric, and seismic reflection data were collected during a four day period. This survey is combined with previous surveys by Oregon State University and other institutions to provide a geophysical interpretation of the Orozco fracture zone and the surrounding area and to develop a tectonic history of the northern Cocos plate.

The Orozco fracture zone is characterized by a typical zone of seismicity and an offset in the magnetic anomaly pattern. There is, however, a conspicuous absence of a well defined topographic trough. This appears to be a result of the small age offset of the ridge crest, a reorientation of the fracture zone trend, and a possible southward migration of the fracture zone down the ridge axis.

Three crustal and subcrustal cross sections over the Orozco fracture zone are constructed from the gravity data. One, across the active portion between the ridge offset, shows the active troughs to be underlain by a broad, low-density root extending two kilometers into the mantle. Two gravity cross sections across the East Pacific Rise show a thinning of oceanic layer 3 of nearly 2 kilometers at the rise crest and a corresponding 0.5 kilometer thickening of layer 2.

A large magnetic anomaly of over 1300 gammas is found at the intersection of the Orozco fracture zone and the East Pacific Rise. A comparison with a very similar observation at the intersection of the Juan de Fuca ridge and the Blanco fracture zone in the northeast Pacific suggests that the East Pacific Rise is "leaking" into the fracture zone in this area.

Many features have been observed on the northern Cocos plate which cannot be accounted for by present Pacific-Cocos motion: the northeast strike of the eastern extension of the Orozco fracture zone, an apparent fanning of magnetic anomalies, and the northeast strike, as well as the origin, of the Tehuantepec ridge. Several possible schemes are examined to explain these observations and all but one are completely eliminated. The proposed explanation supposes a reorientation of the spreading center after a large change in the Pacific- Cocos pole of rotation resulting in the Zed pattern described by Menard and Atwater (1968).

A Geophysical Analysis of the Orozco Fracture Zone and the Tectonic Evolution of the Northern Cocos Plate

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INTRODUCTION

The concept of plate tectonics (McKenzie and Parker, 1967; Morgan, 1968; Le Pichon, 1968) has proven very successful in explaining many of the large scale tectonic features observed globally such as mountain belts, deep sea trenches, and zones of seismicity. The theory supposes that the earth's lithospheric shell is divided into several "plates" which are internally rigid and undergo deformation only at their boundaries. The boundaries consist of three types: 1) constructive, where two plates are moving apart and new crust is being formed (ridges), 2) destructive, where two plates are moving towards one another and one is subducting under the other (trenches), and 3) strike-slip, where only lateral motion takes place. The last type, termed transform faults (Wilson, 1965) or fracture zones, connects one type of plate boundary with another.

One of the outstanding pieces of evidence for sea-floor spreading, of which we will make extensive use, is the symmetric pattern of magnetic anomalies about oceanic spreading centers. As new crust forms at the ridge axes, it becomes magnetized in the direction of the earth's magnetic field. Once the magma cools, its remanent magnetization direction is "locked in" and as the earth's magnetic field reverses polarity, a symmetric pattern of normal and reversely magnetized crust is created about the ridge crest. The effect of the symmetry in the crustal magnetization is to produce a pattern of magnetic anomalies about the ridge crest. In general, the magnetic anomalies are not quite symmetric about the ridge due to the vector field behavior, but if their source is two-dimensional, any phase shift can always be removed by a simple transformation. We will refer to these anomalies as sea-floor spreading anomalies.

With the assumptions of internal rigidity and a constant surface area of the earth, the relative motion between any two plates can be described as a rotation about a unique pole with a given angular velocity. Under these conditions, transform faults are constrained to lie along small circles about the relative pole of rotation between two adjacent plates. In a system of three or more plates, the relative rotation poles cannot remain fixed in any reference frame, and hence the condition of plate rigidity must be substantially relaxed at the plate boundaries (McKenzie and Morgan, 1969; McKenzie and Parker, 1974). This fact is manifested in the observation that the shear zones represented by transform faults are never as structurally simple as their function implies.

Only within the last few years have fracture zones been surveyed in the detail their complexity demands. Even so, very little is still known about their subsurface structure. Two seismically active fracture zones in the eastern central Pacific, the Rivera and the Orozco, have been surveyed in detail by the Geophysics Group at Oregon State University. Both fracture zones are of the ridge-ridge type (Wilson, 1965) and offset the actively spreading East Pacific Rise. A gravity and magnetic interpretation of the Rivera fracture zone was given by Gumma (1973) and a similar analysis of the Orozco fracture zone is the subject of this thesis.

Gravity, magnetic, bathymetric, and seismic reflection data were gathered over the Orozco fracture zone and the surrounding area during a four day period in April, 1974. These data have been combined with data previously collected in the area and are analyzed to obtain the crustal and subcrustal structure of the Orozco fracture zone and the adjacent ridge crests. The combined magnetic data are examined to infer some of the tectonic processes taking place at the intersection of the fracture zone and the ridge crest.

The orientation of the eastern extension of the Orozco fracture zone presents an interesting problem. In between the offset ridge crests, the Orozco forms part of the boundary between the Pacific and Cocos plates. Reliable rotation poles between these two plates indicate that the relative motion is nearly east-west at the Orozco fracture zone; however, the eastern extension of the Orozco has a definite northeast trend. There are other observations which seem unexplainable by current plate motions. For example, the Tehuantepec ridge, located southeast of the Orozco fracture zone, also has a northeast trend and roughly parallels the eastern extension of the Orozco. Furthermore, magnetic anomalies observed over the northern Cocos plate display a large amount (nearly 40^{o}) of fanning, too large to be explained by the current pole position (Lewis _et al._, 1975). These enigmas are answered by reconstructing the tectonic history of the northern Cocos plate during the past 100 million years and are discussed in the final section.

PREVIOUS WORK

Origin of Transform Faults

Several types of transform faults as described by Wilson (1965) have been recognized around the world. As more and more data is collected over active oceanic spreading centers, the number of known ridge-ridge transform faults increases steadily. Occasionally, where one fracture zone was thought to exist from offsets in the sea-floor spreading anomalies or diffuse epicenter locations, more detailed surveys indicate the existence of several en echelon faults (Ramberg et al., in press). Are transform faults due to the geometry of the separating plates at the initiation of spreading or do they come and go as transient features? Certainly the geometry of the initial breakup initiates some transform faults, as attested by the equatorial Atlantic fracture zones, but it is doubtful that this is the only origin.

A thermodynamic explanation for the origin of transform faults has been proposed by Turcotte (1974) and Collette (1974). They suggested that ridge-ridge transform faults are necessary to relieve thermal stresses in the cooling lithosphere. The observation that some transform faults have a graben-type structure similar to rift valleys (Collette and Rutten, 1972) supports this explanation, although rough calculations by Turcotte indicate that the thermal contraction is too small to explain the large widths of most fracture zones.

Another explanation was given by Menard and Atwater (1968). They proposed that during a ridge reorientation caused by a change in the direction of sea-floor spreading, the ridge crest might break into smaller segments so that ridge readjustment occurs in a shorter time and within a smaller area. Hence, increasing the number of transform faults will expedite a ridge reorientation. This may explain the large number of fracture zones in the FAMOUS area (Heirtzler and Ballard, 1975) in the north Atlantic.

Asymmetric sea-floor spreading, such as that observed south of Australia (Weissel and Hayes, 1971), offers another possible origin for transform faults. If a symmetrically spreading ridge segment lies adjacent to a segment which is spreading asymmetrically, the two ridge segments must migrate with respect to one another, creating a ridge-ridge transform fault. Of course, it is also possible for asymmetric spreading to reduce the offset if the spreading direction is such that the ridge segments migrate towards one another.

The jumping of ridge segments may also initiate transform faults, although most known jumps are in a direction to reduce ridge offsets and not to increase or create them (e.g., the Mathematician and Clipperton ridges near the Orozco fracture zone (Sclater et al., 1971)). The observations of asymmetric spreading and ridge jumps suggest that some fracture zones are not perpetual but may only exist as transient features. The Surveyor fracture zone in the northeast Pacific, for example, is a transform fault which eventually closed (Shih and Molnar, in press).

Topography of Fracture Zones

The topographic expressions of fracture zones vary greatly. Many fracture zones are linear troughs, often complex, with accompanying linear ridges, and others exhibit lines of volcanoes, sometimes en echelon (Menard and Chase, 1970). Nearly all fracture zones have widths on the order of tens of kilometers.

As new crust spreads away from the oceanic rises it cools and gradually sinks so that basement depth is a function of age (e.g. Sclater and Francheteau, 1970; Sclater *et al.*, 1971). Adjacent crust offset by a transform fault, because it differs in age, displays a difference in elevation accounting for one type of fracture zone topography (Menard and Atwater, 1969).

Changes in the direction of sea-floor spreading can also produce transform fault topography (Menard and Atwater, 1968; van Andel *et al.*, 1969, 1971). Depending on the sense of the fracture zone offset and the direction of the change in spreading, either rifting or compression can take place across the existing offset. A component of rifting, for example, might cause the development of a topographic ridge in the old fracture zone as a result of an incipient spreading center. van Andel *et al.* (1969, 1971) conclude that this is the cause of some of the topographic features of the Vema fracture zone.

Frequently, a fracture zone is characterized by a bordering ridge or a line of volcanoes such as the Mendocino escarpment in the northeast Pacific. Vogt and Johnson (1975) have proposed a possible mechanism for this type of feature. They suggest that there must be some longitudinal flow of partial melt beneath the spreading axes. Where the ridge is offset, the longitudinal flow will be impeded or arrested altogether by the adjacent thicker lithosphere. Since the plate thickness increases with age (e.g. Christensen and Salisbury, 1975; Parker and Oldenburg, 1973), the most severe impediment results at the largest offsets. Depending on other factors, such as flow intensity, the flow might collect on the "upstream" side of the fault. The larger amount of partial melt would result in a larger discharge of basalt giving rise to volcanic ridges along the boundary. This hypothesis accounts for the topographic offsets across the large Pacific fracture zones whereas the model of Menard and Atwater (1969) cannot adequately provide the observed relief.

A deep trough is often observed at the intersection of fracture zones and ridge crests (e.g. Melson, 1969; Olivet _et al._, 1974). A plausible explanation for this was presented by Sleep and Biehler (1970). The additional surface imposed by the truncation of the spreading center by the transform fault, to which the upwelling magma might tend to "stick," causes an extra loss of hydraulic head in the upwelling viscous magma. Such a loss would manifest itself as a topographic depression. As the plates spread away from the ridges some of the lost head is recovered resulting in a subsequent uplift of topography. This secondary uplift may account for ridges often observed along fracture walls (Sleep, 1969).

Gravity and Magnetics of Fracture Zones

When constrained by seismic refraction, gravity modeling is very useful in studying the crustal and subcrustal structure beneath fracture zones. Dehlinger et al. (1967) conducted the first major gravity survey of a fracture zone. Examining the eastern end of the Mendocino escarpment in the northeastern Pacific they noted that the topography was mirrored by a corresponding offset in the mantle. They concluded that the escarpment is a result of isostatic compensation of juxtaposed mantle material with different densities.

Sibuet et al. (1974) used the same data to examine the thickness of the lithosphere. By examining the gravitational edge-effect produced by different lithospheric thicknesses, they concluded that the thickness is 75 $\pm$ 25 kilometers. Although the uncertainty is large, this result agrees very well with lithospheric thicknesses determined on the basis of heat flow and bathymetric data (Sclater and Francheteau, 1970) and the depth of the low velocity zone (Oliver and Isacks, 1967).

Only a few gravity surveys have been reported over the seismically active portions of fracture zones. In a survey over the Rivera fracture zone, the northern neighbor of the Orozco, Gumma (1973) reported free-air anomalies lower than -110 mgal over the western end near the intersection with the East Pacific Rise axis. The Rivera fracture zone is still in the process of adjusting to Pacific-North America motion (Ness and Lynn, 1975), suggesting that such extreme gravity values may not be typical, although Cochran (1973) reported lows of nearly -100 mgal over the Vema fracture zone in the equatorial Atlantic. From seismically constrained gravity models, Gumma concluded that a low density root of 5 to 7 kilometers must exist directly below the central trough. Gumma also concluded that rocks from layers 2 and 3 appear to outcrop along the steep walls of the central trough.

In a study of the Charlie-Gibbs fracture zone in the north Atlantic, Olivet et al. (1975) noted a -30 mgal low in the free-air anomaly at the junction of the mid-Atlantic ridge and the fracture zone. This seems to be a more typical value for fracture zones. They suggest that this minimum is associated with a basement trough corresponding to the topographic depression model of Sleep and Biehler (1970).

In a general geophysical study of several fracture zones in the equatorial Atlantic, Cochran (1973) found it necessary to include high density material beneath the fracture zones in order to fit the observed anomalies. He concluded that the large fracture zones serve as the site of intrusion of ultrabasic rocks. This result is nearly the direct opposite of Gumma's observation of a low density root under the Rivera fracture zone. The cause of this contradiction may be because Gumma's models are over seismically active portions of the fracture zone whereas Cochran's models are west of the active segments.

In a gravity model across the Panama fracture zone, Barday (1974) noted a shoaling of the Moho beneath the fracture zone. This again contradicts the observation of a low density root; however, Barday suggested that the contradiction may be due to the proximity of two nearby aseismic ridges whose structures are dominating that of the fracture zone.

Fracture zones are often characterized by large magnetic anomalies which appear distinct from the prominent sea-floor spreading anomalies (Rea, 1972). Rea demonstrated that the amplitude of the anomalies is roughly dependent upon the strike of the fracture zone implying a two-dimensional source.

Several authors have reported a large positive anomaly over fracture zones and have proposed intrusive bodies, as well as extrusive accumulates to account for the anomaly (see Gumma, 1973 for a summary). Without recourse to any magnetic bodies within the fracture zone, Gumma successfully modeled the large anomaly across the Rivera fracture zone using a 0.5 kilometer thick layer of remanent magnetic material with depth determined by the surface topography.

A unique source for all fracture zone anomalies appears improbable (Vogt et al., 1971). Because of its inherent mathematical non-uniqueness, magnetic modeling cannot independently resolve the exact source and petrologic and gravity data must be incorporated.

TECTONIC SETTING

The Cocos plate lies just west of Central America and is bounded on the west by the East Pacific Rise, on the south by the Galapagos rift zone and the Panama fracture zone, and on the east by the middle America trench (Figure 1). The Orozco fracture zone is located near 15°N, 105°W, approximately 600 kilometers southwest of Acapulco, Mexico. It offsets the north-south trending East Pacific Rise 95 kilometers in a left-lateral sense and forms a part of the boundary between the Cocos and Pacific plates. North of the Orozco, the East Pacific Rise is offset again by the Rivera fracture zone. From there it continues north into the Gulf of California where it is offset by several en echelon transform faults which lead into the San Andreas fault system. South of the Orozco, the East Pacific Rise is offset at least twice, once by an unnamed fracture zone near 10.5°N and again by the Siqueiros fracture zone, before it intersects the Galapagos rise at the Galapagos triple junction.

The half-spreading rate between the Pacific and Cocos plates in the vicinity of the Orozco fracture zone is approximately 5.0 cm/yr. The present relative motion between the two plates as determined from the Pacific-Cocos pole of Minster et al. (1974) is nearly east-west.

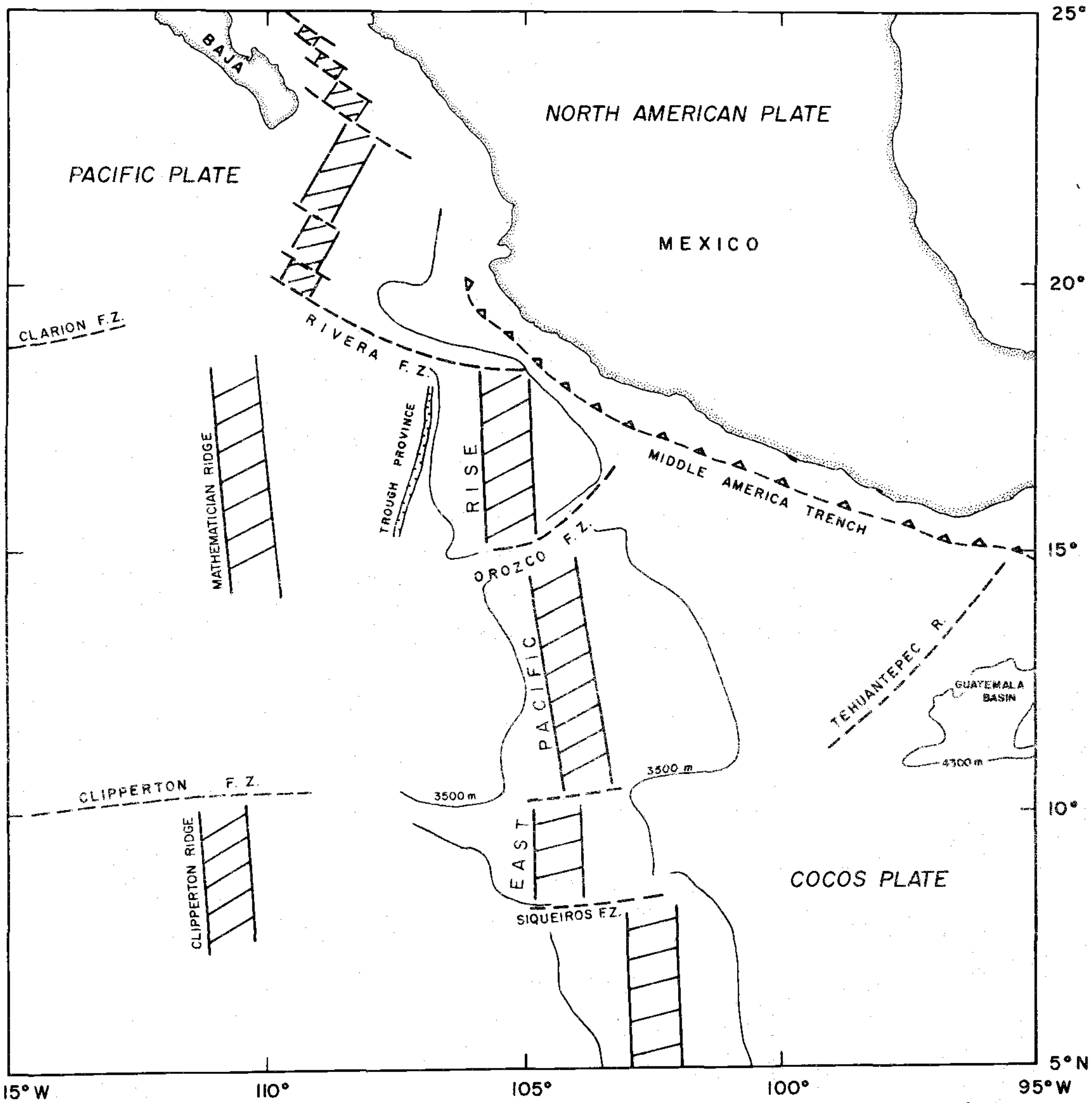

Figure 1. Physiographic map of the Orozco fracture zone area. (3500 and 4300 meter contour taken from Chase et al., 1971)

The eastern edge of the Cocos plate is underthrusting the North American plate at the middle America trench at a rate which varies along the trench from 7.9 to 9.0 cm/yr (Larson and Chase, 1970). The relative direction of motion between the two plates is approximately N50^{o}E.

Although not seismically active, there are several other prominent features in the area. First is the Tehuantepec ridge located southeast of the Orozco fracture zone. Morgan (1972) has suggested that many aseismic ridges and volcanic chains, such as the Hawaiian Island chain, are the result of plate motion over fixed "hot spots" located beneath the lithosphere. Noting the near parallel trends of the Cocos ridge, a proposed hot spot trace, and the Tehuantepec ridge, Herron (1972) suggested that the latter was also a hot spot trace reflecting Cocos-mantle motion. Using gravity models, however, Woodcock (1975) has noted a 3 kilometer offset in the mantle beneath the ridge suggesting it to be a relic fracture zone. This interpretation will be used hereafter.

Also prominent in Figure 1 are the north-south trending Mathematician and Clipperton ridges. On the basis of topography, Sclater et al. (1971) interpreted these ridges as fossil spreading centers between the Pacific and Cocos plates. This interpretation will also be used in a proposed tectonic history of the nothern Cocos plate.

Situated between the Mathematician ridge and the East Pacific Rise is a long, linear trough province with a relief of over 1500 meters. The trough can be traced as far north as the Rivera fracture zone and extends southward to at least the Orozco fracture zone. No explanation has been proposed for this feature.

DATA

Gravity, magnetic, bathymetric, and seismic reflection data were collected over the Orozco fracture zone and surrounding area during a four day period in April, 1974 by the Geophysics Group at Oregon State University. In addition, data have been compiled from five previous Oregon State University cruises through the area. A substantial amount of magnetic data was collected by the University of Washington and the Scripps Institution of Oceanography during an extensive seismic refraction survey of the northern Cocos plate just south of the Orozco fracture zone. This data will be used in a later section on tectonic interpretations.

Figure 2 shows the location of Oregon State University data. The parallel dashed lines represent the axis of the East Pacific Rise and the major troughs of the Orozco fracture zone are shown by the arcuate dashed lines. The tracklines for the four day survey (labelled Y7309) were planned on the basis of bathymetric maps of the north Pacific by Chase et al. (1971). During the four day survey, six traverses were made across the Orozco fracture zone and two long traverses were made across the East Pacific Rise. The trackline spacing across the Orozco averages about 60 kilometers. With the exception of Y69APR, all cruises were navigated by satellite. Fixes

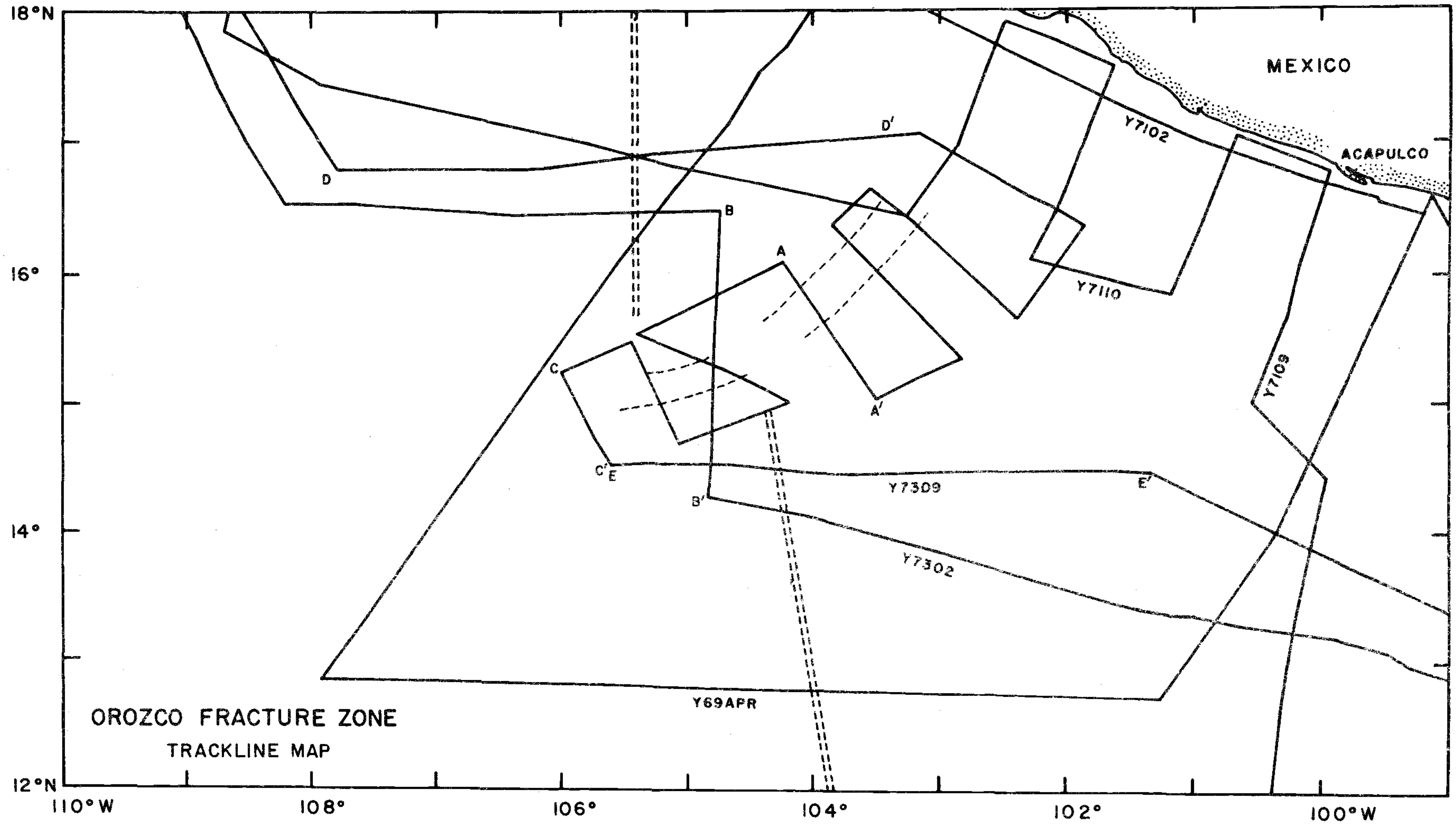

Figure 2. Location map of Oregon State University tracklines in the area of the Orozco fracture zone.

obtained at intervals of less than two hours make the ship's position accurate to within 0.2 kilometers.

On the 71 and 73 cruises, gravity values were recorded using a LaCoste-Romberg surface gravity meter S-42. A LaCoste-Romberg gimbal mounted meter S-9 was used on Y69APR. Cross-coupling corrections calculated in real time at sea were applied to correct for horizontal ship accelerations. The analog gravity records were digitized at five minute intervals, corresponding to a spatial sampling frequency of approximately 0.7 points per kilometer. Gravity meter land ties at accurately measured base stations were made at Rodman Naval Base, Canal Zone, Panama and at San Diego harbor for the Y7309 survey. Estimated accuracy between the base values and the gravity meter are within $\pm$ 1.0 mgal.

Free-air gravity anomalies were computed using the standard formula: FAA = observed gravity + free-air correction - theoretical gravity, where FAA is the free-air anomaly. For gravity measurements at sea the free-air correction is simply zero. The theoretical gravity is a function only of the latitude ϕ and is given by the 1967 Gravity Formula:

$$g = 978031.85(1 + 0.005278895 \sin^2\phi + 0.000023462 \sin^4\phi) \quad \text{(mgal)}.$$

Total magnetic field intensities were recorded using a Geometrics proton-precession magnetometer model G-801 on the 71 and 73 cruises. Prior to 1971, a similar unit by Packard-Varian was used. The Geometrics magnetometer is accurate to 1 gamma. Analog records were digitized at 5 minute intervals. Magnetic anomalies were calculated by subtracting a regional field computed by spherical harmonic analysis. This theoretical field is a function of latitude, longitude, and time and is given by Cain and Cain (1968).

A suspicious feature of the magnetic data is the presence of a positive bias for each cruise ranging from 45 to 175 gammas. This is believed to be caused by inaccurate temporal coefficients of the theoretical field. Consequently, the average level was removed from each cruise resulting in a significant improvement in crossing point errors.

Figure 2 also shows the locations of the gravity profiles used to construct models. Three profiles are across the Orozco fracture zone. Profiles A-A' and C-C' are across the eastern and western inactive extensions of the fracture zone respectively and profile B-B' is across the active portion. Profiles D-D' and E-E' are across the East Pacific Rise. Profile E-E' is of special importance for it is the only profile constrained by seismic refraction data. All other profiles are adjusted to match mass columns with profile E-E'. This will be discussed further in the section on gravity observations.

OBSERVATIONS AND INTERPRETATIONS

Bathymetry

The available data offer seven traverses across the Orozco fracture zone and three traverses across the adjacent segments of the East Pacific Rise. The bathymetric profiles corresponding to these traverses are shown in Figure 3. The profiles have been rotated 35° counterclockwise and tilted upward 30° to give a better perspective along the strike of the Orozco fracture zone. The vertical exaggeration is approximately 10 to 1. The main trough of the fracture zone is denoted by the small vertical arrows. The East Pacific Rise is represented by a peak in the bathymetry indicated by the larger arrows.

The most important observation of the bathymetric profiles across the Orozco fracture zone is the lack of a long, well defined trough. Between the rise offset (profiles 3 and 4), the fracture zone has at least two large troughs reaching a depth of over 3300 meters with a relief of about 1000 meters. Most of the seismicity of the fracture zone is associated with these troughs. The greatest relief, however, is found near the northern end of profile 4 at the intersection of the rise crest with the fracture zone. Here, the depth drops to 4200 meters with a relief of over 1500 meters. Similar topographic

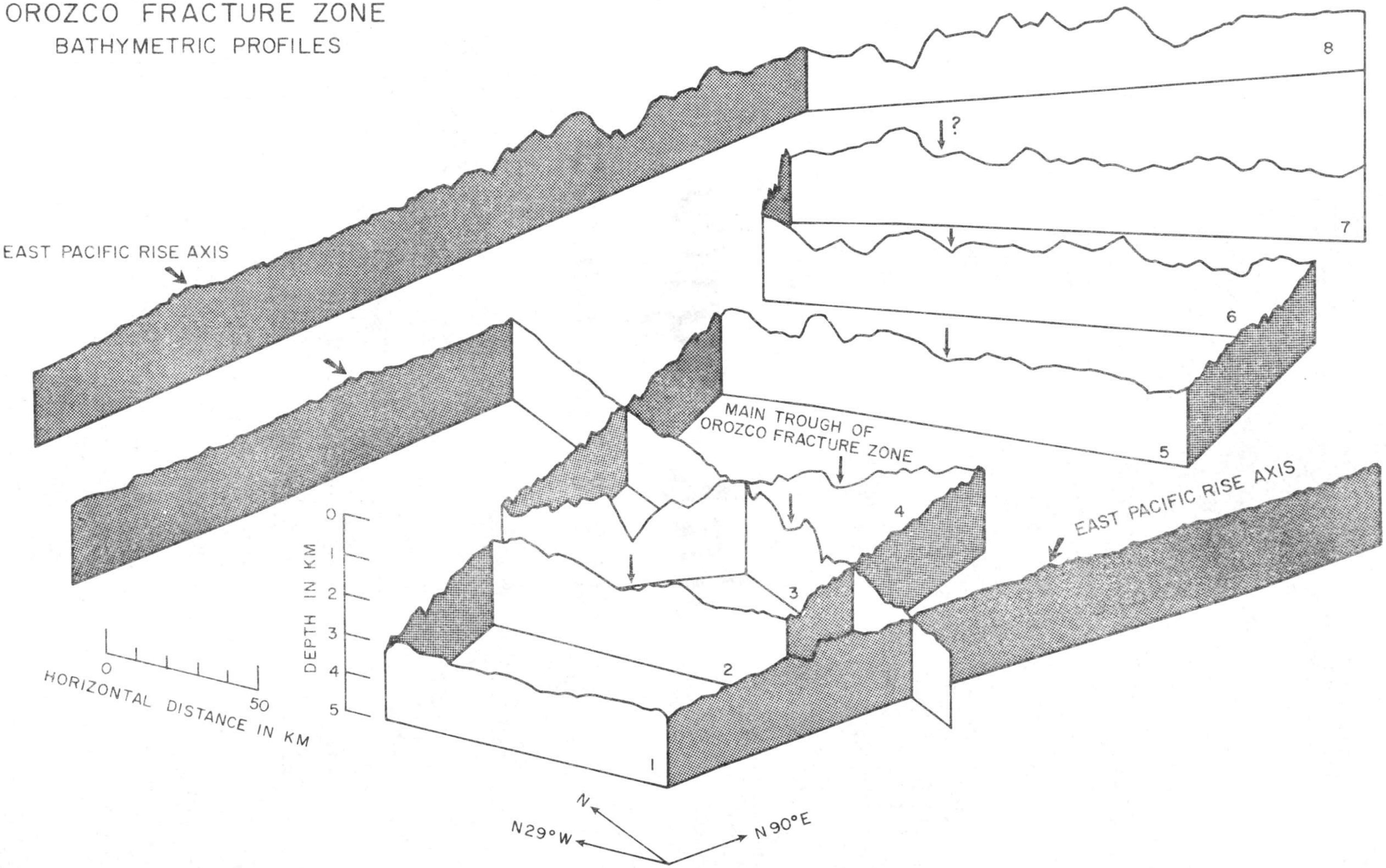

Figure 3. Bathymetric profiles from the Y7302 and Y7309 surveys over the Orozco fracture zone.

depressions at the intersections of fracture zones and ridges have been noted on several detailed studies. In particular, two nearby fracture zones, the Rivera (Gumma, 1973) and the Siqueiros (Crane, 1975), also show a similar topographic depression. This depression is interpreted to be associated with a loss of hydraulic head in the upwelling viscous magma as suggested by Sleep and Biehler (1970). In all three cases, the Rivera, Orozco, and Siqueiros, the deep is located at the fracture zone intersection with the northern rise segment. This coincidence may be related to a uniform direction of longitudinal flow of partial melt beneath the rise axis assuming the model of Vogt and Johnson (1975).

Locating the fracture zone outside of the active segment is tenuous. In fact, 60 kilometers west of the active portion on profile 1, any distinct trough is unidentifiable. East of the active portion, the trough changes strike and is traceable for over 200 kilometers before it merges with the middle America trench. The trackline spacing is too great to discern whether the change in strike is gradual or abrupt. The main trough is paralleled by two other troughs to the north as seen on profiles 5 and 6 which have greater relief than the one marked with the arrows. These may represent the actual inactive eastern extension of the Orozco fracture zone implying that it is migrating southwards along the ridge crest. We will see further evidence for this in the gravity crustal and subcrustal cross sections across the fracture zone.

The East Pacific Rise is well defined on all ridge crossings; however, there is a definite change of character between the segment north and the segment south of the fracture zone. North, the ridge crest is very smooth, whereas south, the ridge crest is much more broken and rough. This is substantiated by ridge crest crossings just south of the area in Figure 3 by the University of Washington and may be due to a ridge reorientation discussed in the tectonic evolution section.

Gravity Anomalies

Free-air Anomaly Contour Map

The free-air gravity anomalies of the Orozco fracture zone and adjacent area were contoured at 10 mgal intervals (Figure 4). The root-mean-square uncertainty in the gravity measurements as determined by trackline crossings is 3.5 mgal, indicating a strong reliability in the measurements.

The main gravity expression of the Orozco fracture zone is shown by the northeast trending linear anomalies beginning near 15°N, 105°W. Although the contours are strongly biased by the trackline geometry (Figure 2), the northeast-southwest trend is believed to be real on the basis of previously charted bathymetric trends (Chase *et al.*, 1971). Because of a lack of gravity data, the

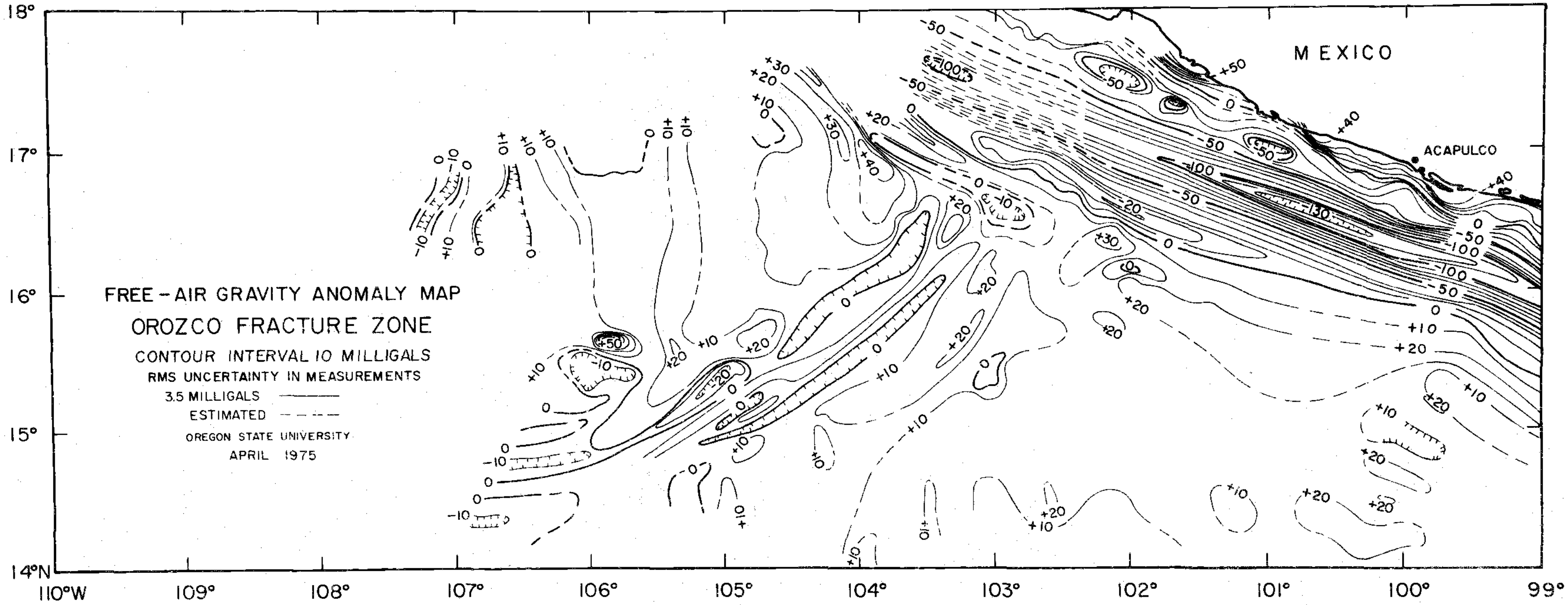

Figure 4. Free-air gravity anomaly contour map of the Orozco fracture zone.

contours at the intersection of the fracture and the trench near 16.5°N, 103°W are inferred on the basis of the bathymetry.

The gravity of the Orozco fracture zone is characterized by two long parallel negative anomalies. At the intersection with the trench, the two lows are slightly bifurcated by a local 30 mgal high. The intersection of the fracture zone with the northern extension of the East Pacific Rise at 15°N, 105°W is characterized by a -24 mgal low associated with the 4200 meter depression noted in Figure 3.

The Cocos plate, both north and south of the Orozco fracture zone, is characterized by positive free-air anomalies. Anomalies observed north (Gumma, 1973) and south (Woodcock, 1975) of the area shown in Figure 4 show a similar positive level. The non-zero free-air anomaly indicates that the Cocos plate is not in isostatic equilibrium. There are at least three possible causes for the regionally high anomalies. First, the positive anomalies may be the outer gravity high observed seaward of trenches caused by a flexure and/or thinning of the oceanic crust (Watts and Talwani, 1974, 1975). Alternatively, the high may be due to a high density mantle near the trench due to phase transitions (Hayes, 1966; Grow and Bowin, 1975). Third, because of the small size of the Cocos plate compared to the bordering Pacific and North American plates, the Cocos plate may be succumbing to stresses exerted by the bordering plates causing the crust to upwarp slightly yielding the positive animalies. Structurally, the first and third causes are indistinguishable, although the latter may extend over a larger area. Woodcock (1975) modeled the gravity across the middle America trench between the Orozco fracture zone and the Tehuantepec ridge and found that the outer gravity high could be explained by a 1 kilometer thinning of the crust favoring the first cause listed above. Many of the local 10 and 20 mgal anomalies on the surrounding plate area are probably of greater extent but cannot be verified due to lack of data.

The ridge axis north of the Orozco fracture zone is characterized by a positive anomaly of about 15 mgal, which is roughly 5 mgal greater than the surrounding anomalies. On profiles south of the Orozco a similar peak is observed (Figure 9; Lu, 1971). This anomaly is discussed with the ridge crest crustal and subcrustal gravity cross sections.

The prominent linear trends in the northeast corner of the map are associated with the middle America trench and are parallel with the trench axis. The free-air anomaly reaches a low of about -130 mgal along the axis of the trench. With the exception of a few local lows, which are probably sediment basins (Woodcock, 1975), the continental shelf is characterized by positive anomalies.

Two other features are noteworthy. First is the indication of two north-south parallel troughs in the vicinity of 17°N, 107°W. These are associated with the trough province noted in Figure 1.

Second is the local 50 mgal high at 15.7°N, 105.9°W. This anomaly is caused by a large seamount situated just west of the East Pacific Rise crest.

Crustal and Subcrustal Cross Sections across the Orozco Fracture Zone

It is well known that the inversion of potential field data, such as gravity, to find the source is inherently nonunique. However, when constrained by seismic refraction, petrologic, and other geophysical data, the forward process of modeling can reveal the gross structure of the source or at least set bounds on the possibilities. The average value of the anomaly produced by any gravity model can be arbitrarily changed by adding or subtracting a horizontal slab of infinite horizontal extent. Barday (1974) constructed a standard oceanic section which has a gravitational attraction of 6442.0 mgal and we have used this value to be the 0 mgal level in our cross sections. It will be seen in the following discussions on the gravity models that the main effect of this constraint is to fix the mantle density.

All of the models generated were assumed to have a compensation depth of 50 kilometers as in Barday's standard section. It is implied, then, that below this depth there are no lateral variations in the mantle. Across the fracture zone this is probably a good assumption; across the rise crest the assumption is less tenable, but not without support. Talwani et al. (1965) concluded on the basis of the steep gradients of the Bouguer anomaly across rise crests that most of the lateral variation in density must take place above 40 kilometers depth.

Seismic Refraction Control and Layer Densities. Early seismic refraction studies suggested that the ocean crust was surprisingly uncomplicated, characterized by three distinct layers (Raitt, 1963). Although more recent seismic refraction studies, as well as the wide variety of rocks dredged from the ocean floor, indicate a much more complicated structure, the three layer crustal model appears to be adequate for gravity modeling.

Layer 1 is composed of sediments with velocities ranging from 1.5 to approximately 3.5 km/sec and is usually less than 1 kilometer thick. Layer 2 generally has a thickness of 1.0 to 2.5 kilometers although its velocity is highly variable ranging from 3.5 to 6.4 km/sec (Christensen and Salisbury, 1975). This layer is considered to be composed of tholeiitic basalt grading downward to a low grade metabasalt (Aumento, 1968; Kay et al., 1970). Layer 3 is the thickest of the layers, although its thickness varies considerably between about 3.4 and 6.3 kilometers. Layer 3 velocities are not as scattered and lie within a range of 6.4 to 7.7 km/sec (Christensen and Salisbury, 1975). The composition of layer 3 is more controversial and several different lithologies have been proposed for it. Hess (1962) proposed a composition of serpentinized ultramafics citing the abundance of serpentinite at the ocean ridges as evidence. Using seismic refraction, Cann (1968) suggested that layer 3 is formed by the metamorphism of basalt to amphibolite. Similarly, Oxburgh and Turcotte (1968) proposed a gabbroic or metagabbroic composition of the lower crust. On the basis of compressional and shear wave velocities, Christensen and Salisbury (1975) feel the first two can be dismissed and conclude that only hornblende rich metagabbros have high enough compressional and shear wave velocities to be consistent with those observed in layer 3. Since this composition cannot explain all the observed lithologies, however, they propose that hornblende metagabbros predominate only in the upper levels of layer 3 and unmetamorphosed gabbros predominate in the lower levels.

Five gravity crustal and subcrustal cross sections were considered, three across the Orozco fracture zone and two across the East Pacific Rise (Figure 2). Seismic refraction control was available only for profile E-E' for which three stations were available. All are located south of the profile and are listed in Table 1. Station 3 is an average of two reversed orthogonal lines. The seismic refraction stations were projected onto the profile parallel to the isochrons which is valid assuming little or no change in structure between lithosphere of the same age.

Converting the compressional wave velocities, v_p, into densities was done using the v_p vs. density curve of Ludwig et al. (1970). Seismic reflection records of the Orozco fracture zone area show very little sediment cover even though more than 100 meters of sediment is reported at stations 1 and 2 in Table 1. For this reason, layer 1 was not included in the gravity models. The first large horizon below the water is a 5.0 to 5.2 km/sec layer identified as oceanic layer 2 to which we have assigned a density of 2.6 gm/cc. The next horizon, layer 3, has velocities ranging between 6.7 and 7.0 km/sec to which we have given a density of 2.84 gm/cc. This density is about 0.06 gm/cc lower than expected from the lithologies discussed earlier for layer 3 because of the proximity of the profiles to the ridge crest.

Since the thicknesses and densities of the other layers are known and since the 0 mgal level is constrained to be 6442.0 mgal from the standard section, the mantle density can be determined without recourse to its composition. The mantle densities thus computed are 3.26 and 3.27 gm/cc for the fracture zone cross sections. Although these densities may be incorrect, proceeding in this manner allows a comparison with gravity cross sections from other areas to give at least a semi-quantitative comparison of relative densities. For the two cross sections across the ridge crest, the mantle was considered to have a density of 3.32 gm/cc with a low

Table 1. Seismic Velocities and Layer Thickness.

Station	Location	Water		Sediment		Upper Crust		Lower Crust		Mantle	Total T	Source
		V	T	V	T	V	T	V	T	V	ΣT	
1	10°53'N 104°46'W	1.5	3.14	2.15	0.13	4.97	0.85	6.71	4.33	8.24	8.45	Shor *et al.* (1970)
2	11°38'N 103°48'W	1.5	2.94	2.15	0.15	5.02	1.47	7.04	3.49	7.77	8.05	Shor *et al.* (1970)
3**	13°32'N 102°56'W	1.5	3.2			5.1	0.20	6.87*	4.50*	7.94	7.90	Snydsman *et al.* (1974)

V = Velocity in km/sec
T = Thickness in km

*Includes two layers, 3A and 3B, of 6.5 and 7.1 km/sec.

**Average of two orthogonal, reversed lines.

density pocket of 3.21 gm/cc beneath the ridge axis after Talwani _et al._ (1965).

All of the models are assumed to be two-dimensional and this criterion is examined for each profile. Anomalies were computed for the two-dimensional models by evaluating a line integral around the body (Hubbard, 1948) using the method of Talwani _et al._ (1959). Profiles A-A', B-B', and C-C' run north to south across the Orozco fracture zone and profiles D-D' and E-E' run west to east across the East Pacific Rise. To provide some constraint on the fracture zone profiles, their mass columns and crustal layer depths were forced to match with profile E-E' at their respective intersections with E-E'. Profile D-D' is not seismically constrained and simply uses E-E' as a starting model.

Profile A-A'. Profile A-A' is located 100 kilometers east of the active portion of the Orozco fracture zone (Figure 2). The profile is 150 kilometers long extending from 2.5 m.y. old crust north of the fracture zone to 3.5 m.y. old crust to the south. From Figure 4 we see that the free air anomalies are sublinear, striking roughly orthogonal to the trackline. The assumption of two-dimensionality thus seems to be valid, at least over the fracture zone.

The crustal and subcrustal cross section along A-A' is shown in Figure 5. The observed free air anomaly is given by the solid line at the top. The open circles are the anomalies computed from the

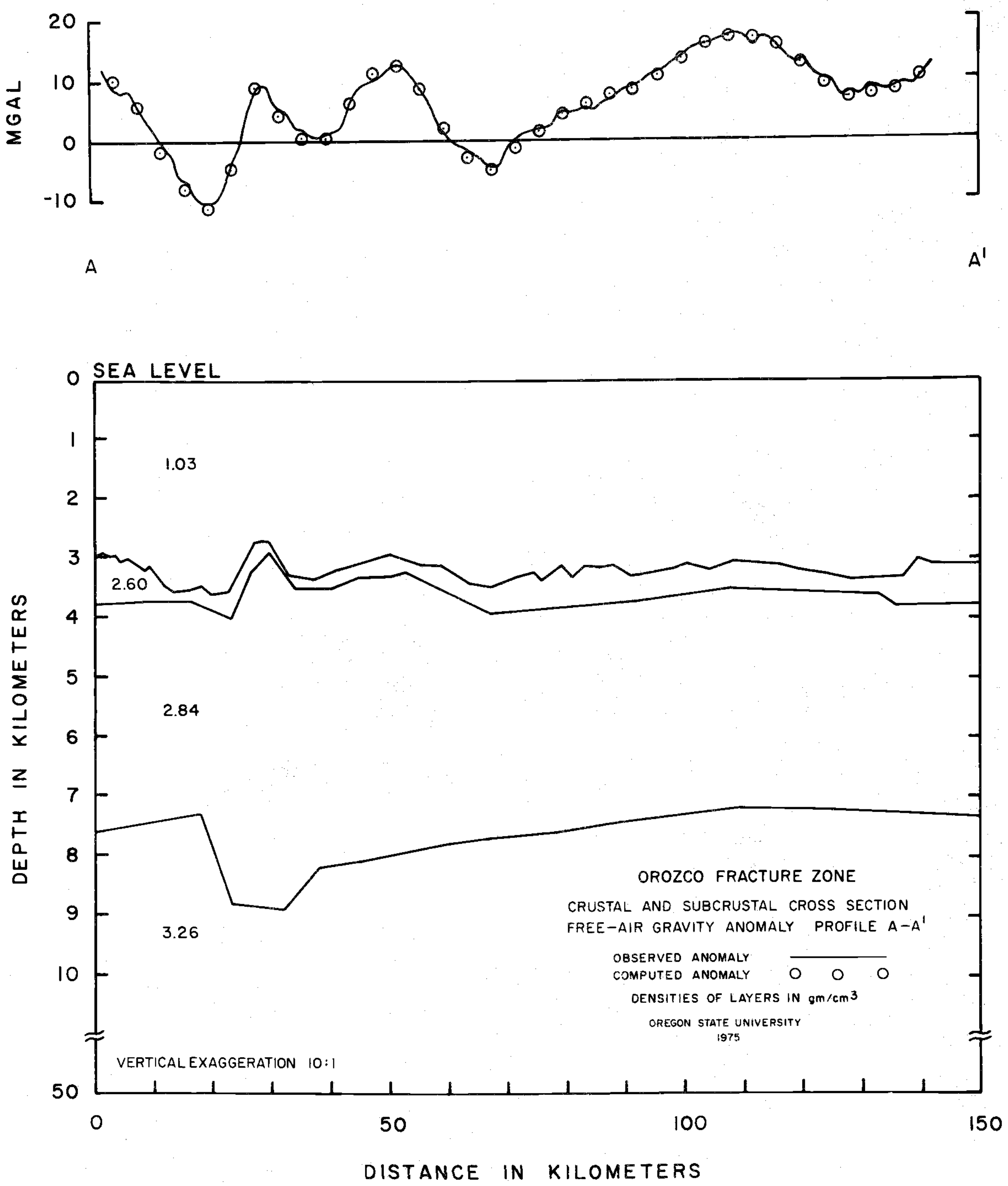

Figure 5. Gravity profile A-A' over the eastern extension of the Orozco fracture zone.

model below and fit the observed anomaly to within 2 mgal. The model has a compensation depth of 50 kilometers, although no lateral variations occur below 9 kilometers. The vertical exaggeration is 10 to 1. Edge effects were minimized by extending the model 20,000 kilometers on both sides.

As noted in Figure 4, the gravity expression across the fracture zone is not overwhelming. The peak-to-peak amplitude is less than 30 mgal. The inactive extension of the fracture zone marked in Figure 3 is located near 65 kilometers from point A, although the actual main trough may be nearer to 30 kilometers.

The top layer of the model is, of course, the water layer with a density of 1.03 gm/cc. The 2.60 gm/cc layer just below is interpreted as oceanic layer 2. The interface between the two was taken as the bathymetry. The lack of sediment on the seismic reflection profiles warranted the omission of layer 1 from the model. The 2.84 layer represents oceanic layer 3. The mantle density, 3.26 gm/cc, was computed by matching mass columns where profiles A-A' and E-E' would intersect if A-A' were extended.

In general, the crust is somewhat thinner than "normal" oceanic crust; however, this is consistent with its young age and isostatic arguments (Christensen and Salisbury, 1975). Over the fracture zone layer 2 thins from 0.7 kilometers to a minimum of less than 0.1 kilometers. This is necessary to fit the short wavelength (20 kilometers) anomalies between 10 and 50 kilometers from point A. Gumma (1973) noted a similar thinning of layer 2 across the Rivera fracture zone and interpreted the cause to be brecciation of material due to the strike-slip motion between the Rivera and Pacific plates. This interpretation is also valid for the thinning observed across the Orozco fracture zone and is discussed in detail in the following section.

The Moho lies at a depth of 8.1 kilometers north and 7.5 kilometers south of the fracture zone (outside of Figure 5). Thus, the crust thickens by roughly 0.6 kilometers from south to north across the fracture zone which is consistent with previous observations of the thickening of oceanic crust with age (e.g. Le Pichon et al., 1965; Le Pichon, 1969; Goslin et al., 1972).

There is a general thickening of layer 3 under the fracture zone area aside from the overall thickening mentioned above. The most prominent feature of this thickening is a small 1.0 kilometer root beneath the large hill at 28 kilometers. This thickening is necessary to isostatically compensate this structure. Alternatively, the Moho could be modeled as a level gradient but with a low density zone beneath the hill. Such a model is not unrealistic as Christensen and Salisbury (1975) note that compressional wave velocities are often lower under fracture zones due to the intense brecciation. As this observation applies mainly to layer 2 and since the profile lies outside of the active portion of the fracture zone, such a model was not considered.

Profile B-B'. Profile B-B' is located across the active portion of the Orozco fracture zone (Figure 2). The profile lies 60 kilometers east of the rise axis on 1.3 m.y. old crust north of the fracture zone and 55 kilometers west of the rise axis on 1.2 m.y. old crust south of the fracture zone. Undoubtedly, two-dimensionality is a poor assumption outside of the fracture zone. However, this will not drastically affect the conclusions about the fracture zone structure. Note that the trackline does not lie perpendicular to the gravity lineations, but makes about a 30° angle with them. Again this will not affect the main results of this model.

The observed free air anomaly and the crustal and subcrustal section along B-B' is shown in Figure 6. Again the observed anomaly is given by the solid line and the calculated anomalies by the open circles. The model is 250 kilometers long with a compensation depth of 50 kilometers, although no lateral variations are modeled below 10 kilometers. The vertical exaggeration is 10 to 1. The model is extended 20,000 kilometers on both sides to remove edge effects.

Although greater than A-A', the gravity expression in profile B-B' is still less than 40 mgal peak to peak, which may be typical for fracture zones. The main trough of the fracture zone is located at 150 kilometers from point B and is superimposed upon a slight

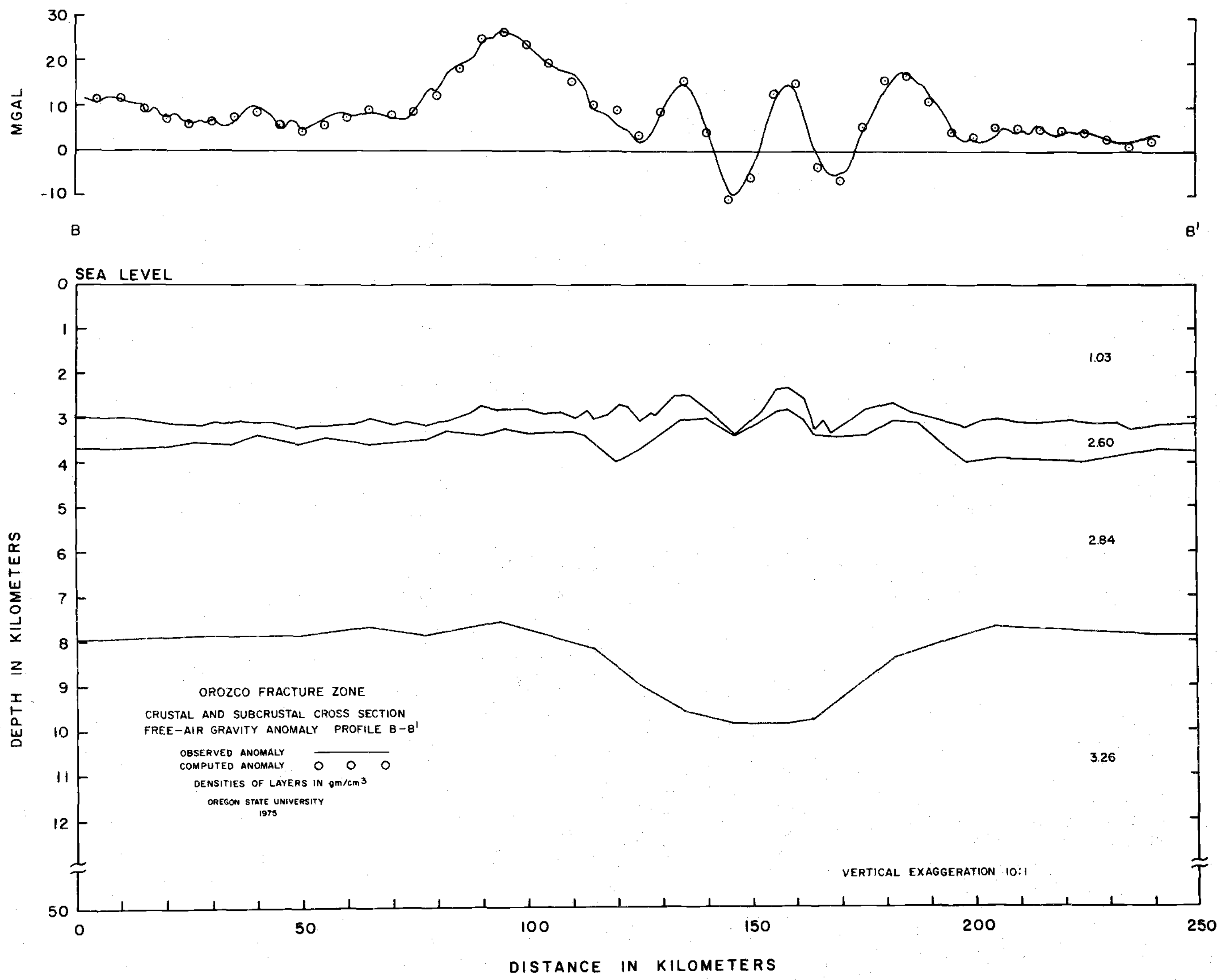

Figure 6. Gravity profile B-B' over the active portion of the Orozco fracture zone.

topographic high of about 0.5 kilometers. The layers are the same as in profile A-A'. The mantle density was computed, as before, by balancing mass columns at the intersection of B-B' and E-E'.

The most pronounced feature of this model is the low density root centered at 150 kilometers and extending nearly 2 kilometers into the mantle. Gumma (1973) noted a similar, but much deeper low density root under the main trough of the Rivera fracture zone. The larger size of the Rivera fracture zone root, however, might be anomalous since the Rivera is still in the process of reorienting itself to become parallel with Pacific-North American motion (Ness and Lynn, 1975).

Brecciation and hydrothermal alteration of mantle material is certainly a likely cause for the low density root and may also explain the local topographic high observed around the trough (Gumma, 1973). Gumma proposed that hydrothermal circulation in the fracture zone made possible by the severe brecciation of material causes a low-grade metamorphism (serpentinization) to take place. The metamorphosed rocks, having lower density, are isostatically uplifted causing the topographic high around the fracture zone trough.

The width of the low density root beneath the active trough is nearly 60 kilometers and is undoubtedly too wide to be accounted for by one fault zone. This implies that the fracture zone has not remained stationary with respect to the ridge, but has migrated and/or reoriented during its recent history.

Layer 2 thins from a thickness of 0.6 kilometers to zero in the vicinity of the main trough. The thinning is necessary in order to fit the low wavelength anomalies observed over the trough, although some of the high frequency content of the anomalies is probably due to imperfect two dimensional structure. In fact, a close comparison of the calculated and observed anomalies shows that even with the thinning of layer 2 the anomalies still cannot be matched precisely.

Because of the poor approximation to two-dimensionality outside of the fracture zone, little reliance can be placed on the structure and hence no comparisons will be made between the north and south ends of the profile.

Profile C-C'. Profile C-C' is located 60 kilometers west of the active portion of the Orozco fracture zone (Figure 2). The profile extends from 1.6 m.y. old crust north of the fracture zone to 3.5 m.y. old crust to the south. Figure 4 shows that two-dimensionality is a good approximation in this vicinity across the fracture zone.

It is not clear where the fracture zone lies on this profile. It is assumed to lie in the northern half on the basis of Figure 3. It is apparent from Figure 7 that the gravity expression is minimal along this profile indicating isostatic equilibrium. The peak-to-peak anomaly is less than 15 mgal.

The layers in the model are the same as in profile A-A', except the mantle density is 0.01 gm/cc higher. The depths of the

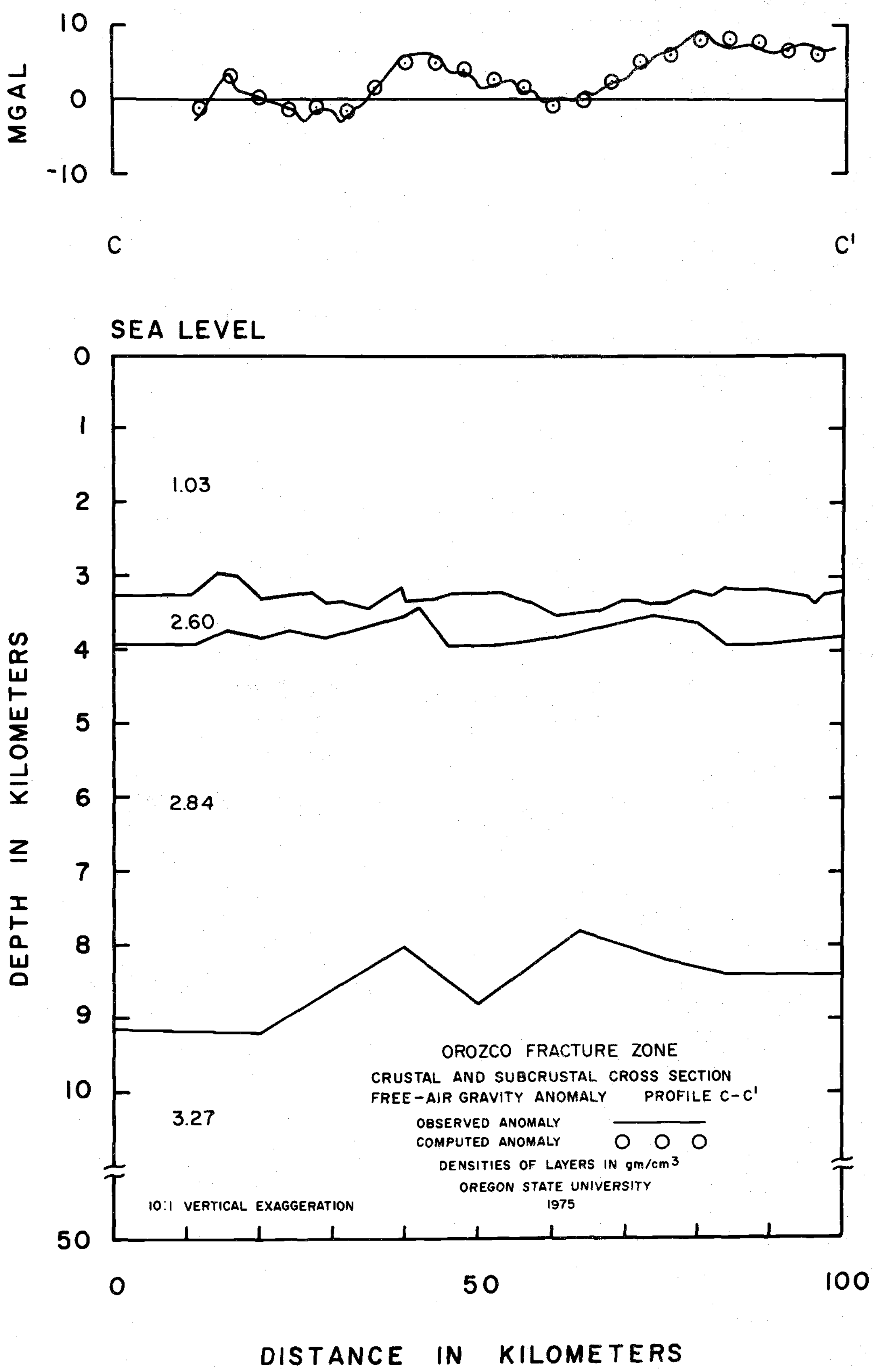

Figure 7. Gravity profile C-C' over the western extension of the Orozco fracture zone.

layers on the southern end of the profile are constrained by the corresponding depths of E-E' where the two profiles intersect.

The most important observation of this model is the shoaling of the Moho between 20 and 85 kilometers with a central root near 50 kilometers. This configuration is necessary, along with some adjustments in layer 2, to offset the effect of the topography, that is, provide isostatic compensation. The small root at 50 kilometers is not unlike the roots observed in A-A' and B-B'. However, the lack of any trough in the bathymetry directly above makes the root suspect as being representative of the fracture zone location.

From north to south across the profile layer 3 thins nearly 0.7 kilometers. This contradicts the thickening of layer 3 with age and may be caused by a lack of two-dimensionality at the ends of the profile.

<u>Crustal and Subcrustal Cross Sections across the East Pacific Rise</u>

<u>Profile E-E'</u>. Profile E-E' lies at 14.5^{o}N and extends from 105.6^{o}W to 101.4^{o}W, or roughly 450 kilometers (Figure 2). The profile crosses the axis of the central anomaly at 104.3^{o}W or at 180 kilometers from point E in Figure 8. It was first necessary to project both the bathymetric and gravity profiles onto a line perpendicular to the ridge crest since the trackline is about 10^{o} oblique to an

orthogonal crossing. It is not clear from Figure 4 if the assumption of two-dimensionality is valid or not. However, other bathymetric profiles to the south over the ridge show that the ridge is linear and not offset again until 10.5°N. On this basis, we assume that two-dimensionality is a justified assumption.

Profile E-E' is the only cross section constrained by seismic refraction. Three stations were used and are listed in Table 1. Station 1 lies west of the East Pacific Rise axis over 2.5 m.y. old crust, station 2 is situated directly on top of the rise crest over virgin crust, and station 3 lies east of the rise axis over 2.8 m.y. old crust (Figure 8).

The observed free-air anomaly is shown as the solid line at the top of Figure 8. With the exception of a small segment at the western end, the anomalies are positive everywhere. Over the rise axis, there is a 5 mgal peak superimposed upon a somewhat flat 5 mgal section. East of the rise axis the anomaly is characterized by a wavelength of about 80 to 100 kilometers with a mean level of approximately 12 mgal. This contrasts with the west side of the rise crest where the wavelengths are about 10 to 30 kilometers. The positive anomalies east of the rise axis, as discussed with the free-air anomaly contour map, are probably associated with the outer gravity high of the subduction zone.

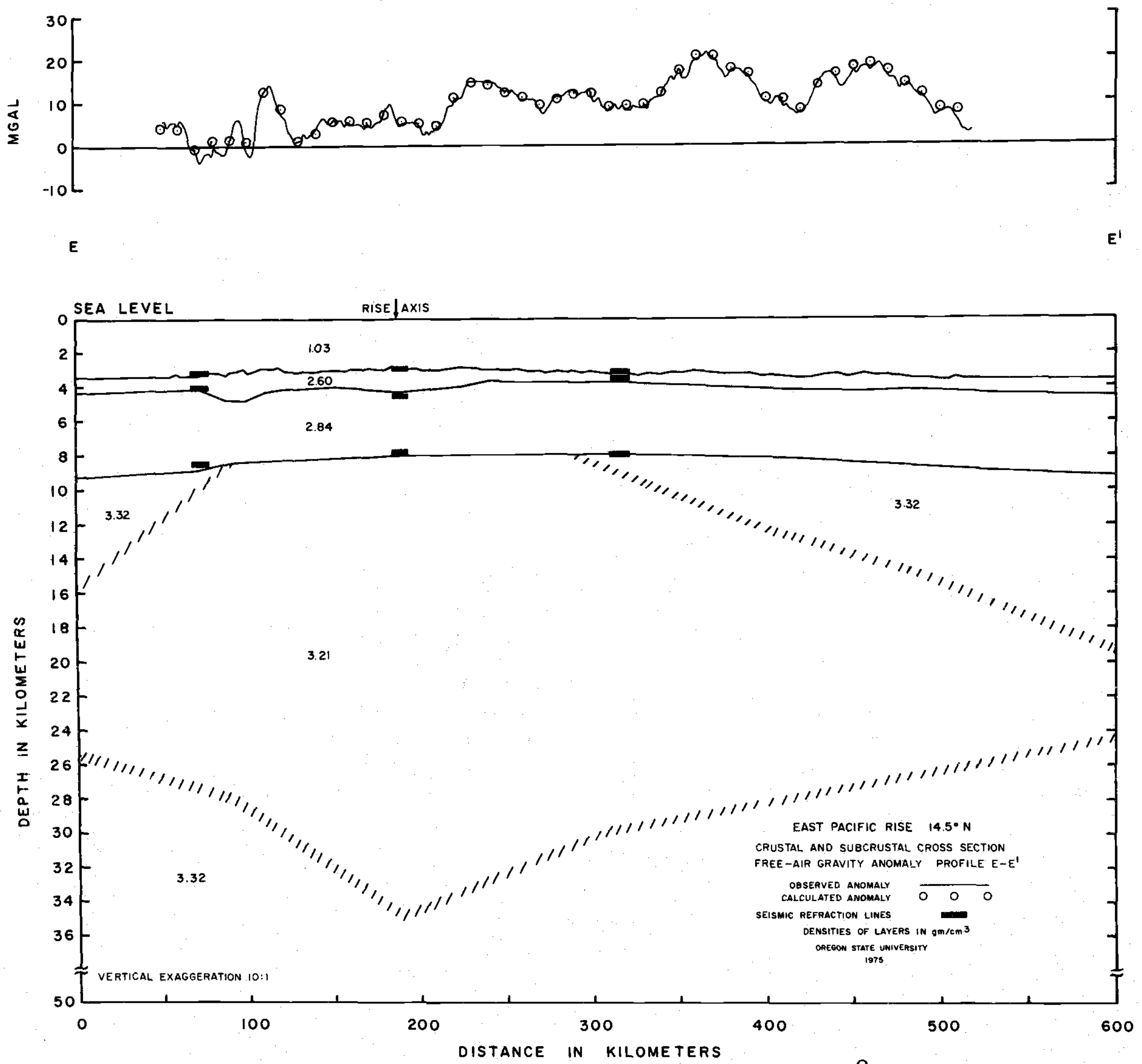

Figure 8. Gravity profile E-E' over the East Pacific Rise at 14.5°N. Seismic refraction stations given in Table 1.

The model shown in Figure 8 is based on previous ridge crest models by Talwani et al. (1965) and Lu (1971). Two mantle densities are used, 3.21 gm/cc for the low velocity zone and 3.32 gm/cc for the "normal" mantle. The 3.21 gm/cc density is somewhat arbitrary and changing it would simply reduce or increase the size of the layer. For this reason the boundary between the two mantle layers is not drawn as a solid line, but dashed instead.

The presence of a low density zone beneath oceanic spreading centers is well known. Seismic refraction studies reveal a lower velocity mantle beneath the ridge crest (e.g. Talwani et al., 1965). Solomon (1973) noted that teleseismic shear waves which pass 50 to 150 kilometers beneath the mid-Atlantic ridge are severely attenuated. He interprets this region of low Q values to be a zone of extensive partial melt. The observation of high heat flow values near ridge crests (e.g. Sclater et al., 1971) also implies a lower density material below. As for the depth extent of the low density zone, Talwani et al. noted that in order to satisfy the steep gradients in the Bouguer anomalies across the mid-Atlantic ridge, it is necessary to have a shallow zone of low density. The size of the layer is unfortunately indeterminate since it is dependent on the density.

Undoubtedly, the model shown in Figure 8 is a gross oversimplification, but it still can provide some of the more general features of the overall structure. First, layer 3 decreases in thickness by nearly 2.0 kilometers as it crosses the rise axis. A similar decrease in layer 3 thickness over the East Pacific Rise was observed by Talwani et al. (1965) and by Lu (1971). At the rise axis, layer 2 thickens by nearly 0.5 kilometers. This is a necessary part of the model in order to subdue the low wavelength anomaly caused by the rise crest. Away from the rise axis, layer 2 is modeled with a fairly uniform thickness of 0.5 kilometers.

Although the profile does not extend far enough westward, there is a strong suggestion of asymmetry in the low density zone. It appears to extend much farther to the east, implying a faster spreading rate in this direction and an examination of the bathymetric map of the area (Chase et al., 1971) lends some support to this. The 3500 meter contour in Figure 1 flanking the East Pacific Rise is nearly twice as far from the axis to the east than it is to the west. Since depth is a function of age (Sclater et al., 1971), this supports asymmetric spreading. The obvious means of checking the proposed asymmetric spreading is to examine the magnetic anomalies. Data coverage west of the rise is not very dense, although tentative correlations made by Herron (1972) and data presented by Sclater et al. (1971) indicate symmetric spreading for at least the last 4 m.y. To resolve this apparent contradiction will require a more detailed magnetic survey west of the East Pacific Rise.

Profile D-D'. Profile D-D' lies at 17°N and runs from 107.8°W to 103.4°W (Figure 2). It intersects the ridge axis at 105.4°W or approximately 260 kilometers from point D. The western end of the profile extends across the trough province noted in Figure 1. The eastern end is truncated before it meets the middle America trench, although the effect of the trench related structure is still pronounced. Again the assumption of two-dimensionality must be considered. The contour map in Figure 4 shows the assumption to be valid west and over the rise crest. However, at the eastern end, the north-south lineations blend into the northwest-southeast orientation related to trench structure. This part of the model must be viewed with caution.

The observed free-air anomaly is given by the solid line at the top of Figure 9. Over the rise crest, the anomaly is very similar to the previous section. The anomaly is generally positive with a small negative segment on the west side. Over the rise axis, there is a 10 mgal peak superimposed upon a somewhat flat positive anomaly of about 8 mgal. The two large peaks near 50 and 100 kilometers are associated with the trough province. West of the trough province the anomaly is strictly negative. East of the rise axis, the anomaly increases nearly monotonically out to 400 kilometers, where the anomaly is affected by shallow trench structure indicated by the short wavelengths of the anomalies.

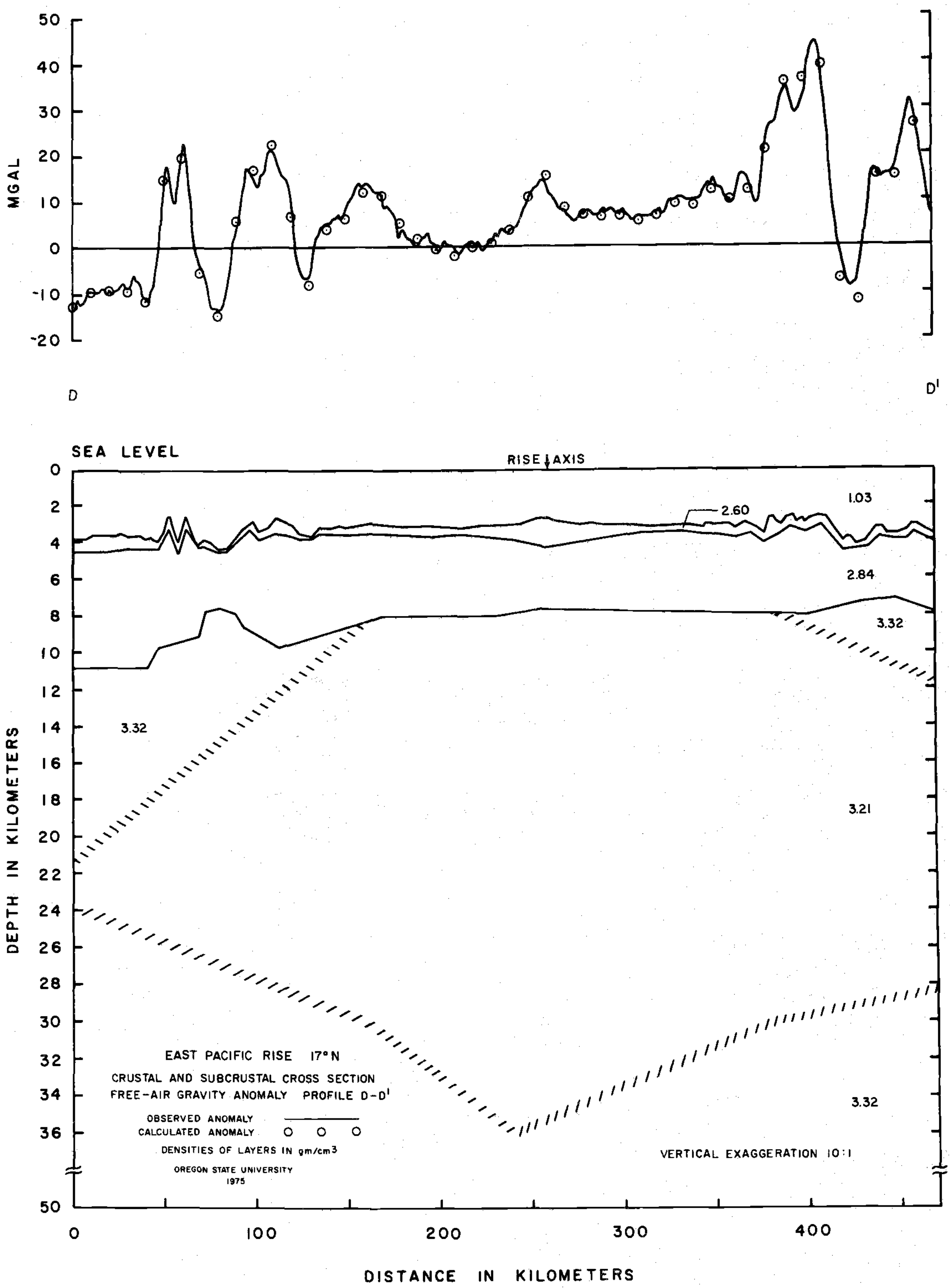

Figure 9. Gravity profile D-D' over the East Pacific Rise at 17°N.

The model shown in Figure 9 has no seismic refraction control and is based entirely on the general structure of profile E-E'. The layers and their densities are the same as discussed in E-E'. As at 14^{O}N, the crust thins over the rise axis. This thinning is more pronounced when approaching the rise crest from the west. Eastwards, the trench is probably disturbing the normal spreading pattern. The inverse relationship between the thicknesses of layers 2 and 3 is again evident. Because of the lack of seismic refraction control it is not absolutely necessary for layer 3 to thin. However, layer 2 must thicken in order to compensate for the large, short wavelength topographic expression of the rise crest.

Under the trough province between 50 and 100 kilometers, a 2 to 2.5 kilometer antiroot is necessary to compensate for the deep depression. The higher frequency of the anomaly also requires some thinning of layer 2. Across the trough province, the Moho is offset nearly 3 kilometers suggesting a possible age offset in the crust.

The eastern end of the model is not as reliable due to the presence of the northwest-southeast trending trench structure. This might explain, at least in part, the poorer fit of the calculated anomalies with those observed. To a large extent, the gravity can be fit with a 0.5 kilometer layer 2 following the topography and a slight upwarp in the mantle near 440 kilometers.

The two mantle layers are the same as those discussed in the previous model. There is a slight suggestion of some asymmetry in the 3.21 gm/cc layer, similar to profile E-E'. However, due to the lack of seismic control, little confidence can be placed in this observation.

Magnetic Anomalies

Magnetic Anomaly Contour Map

The magnetic anomaly values from six Oregon State University cruises in the Orozco fracture zone area were contoured at 100 gamma intervals (Figure 10). With the exception of a few localized anomalies, the magnitude is generally less than 200 gammas. The most outstanding feature of the map is the lineations associated with the sea-floor spreading anomalies. There is a noticeable change in strike between the lineations north and south of the fracture zone. North, the lineations are almost due north, whereas to the south, the trend is more northwesterly. This observation will be discussed in more detail in the tectonic evolution section.

The central anomaly, delineated by the Brunhes-Matuyama reversal boundary, is closely approximated by the U-shaped 0 gamma contour over the ridge crest north of the fracture zone. South of the fracture zone, the central anomaly is not as obvious on the contour map, although it is very apparent on the magnetic anomaly correlation map (Figure 11).

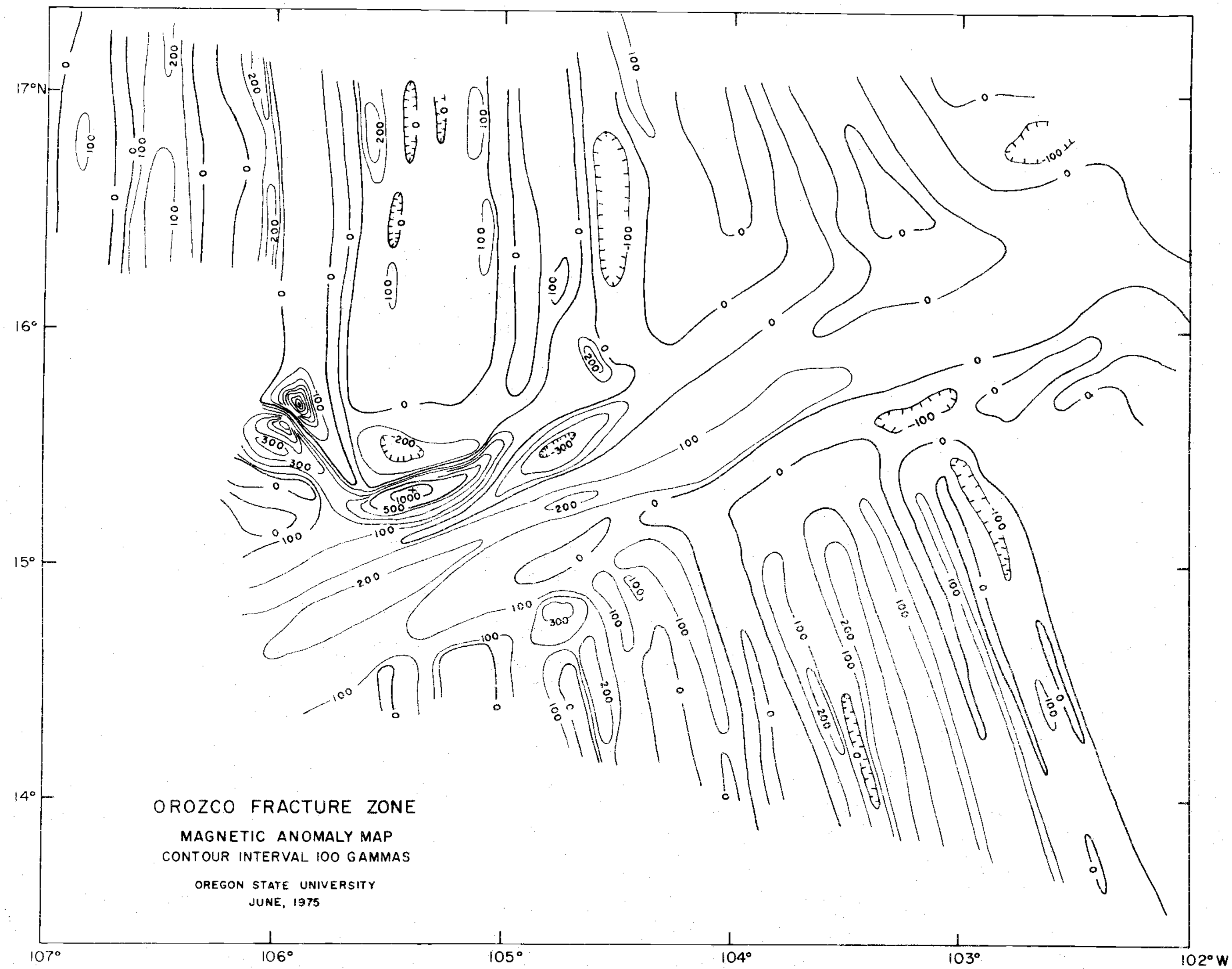

Figure 10. Magnetic anomaly contour map of the Orozco fracture zone area.

The fracture zone is characterized by a positive peak of 100 to 200 gammas running subparallel with the central bathymetric trough. This is consistent with previous observations of a large positive peak over fracture zones. Various explanations have been proposed for this anomaly, most of which invoke either extrusive bodies of intrusive accumulates with either remanent or induced magnetization. Without recourse to any added magnetic bodies, Gumma (1973) successfully modeled the large positive anomaly over the Rivera fracture zone by taking into account topographic effects and using only the remanent magnetization provided by the spreading oceanic crust. No magnetic modeling was done over the Orozco fracture zone, although we feel that the positive anomaly over the trough is probably small enough to be accounted for by topography and we thus favor Gumma's interpretation for the source.

There are two large amplitude anomalies on the map, one at 15.5°N, 105.9°W and the other at 15.2°N, 105.4°W. The former has a maximum of more than 600 gammas with an adjacent low of less than -700 gammas. The bathymetry shows the anomaly to be underlain by a large seamount which is undoubtedly the cause of the anomaly.

The second anomaly lies at the intersection of the fracture zone and the northern extension of the East Pacific Rise and reaches a maximum of over 1300 gammas. The deep trough shown in Figure 3 lies nearly 35 kilometers to the east. An almost identical situation is found at the intersection of the Juan de Fuca ridge and the Blanco fracture zone (Melson, 1969). Here, a 1600 gamma anomaly is situated at the intersection of the ridge and the fracture zone. The bathymetry of this area shows that a deep depression underlies the anomaly area; however, the deepest part of the trough lies nearly 40 kilometers to the east. Using three-dimensional magnetic models and petrologic data from dredge hauls, Detrick and Lynn (1975) concluded that the anomaly is caused by a large body of high magnetization (0.035 emu/cc) which had leaked out of the Juan de Fuca ridge during recent time and filled the western end of the trough. The striking similarities between the bathymetry and the magnetic anomaly patterns between the two areas suggests a similar source for the large anomaly observed in Figure 10.

The leaking of fresh basalt into the Orozco fracture zone may be a result of the longitudinal flow of partial melt beneath ridge axes as proposed by Vogt and Johnson (1975). Alternatively, the leaking may be related to the migration of the fracture zone along the ridge axis as implied by the bathymetry and the broad, low-density root located under the active portion of the fracture zone, a topic we will return to later.

TECTONIC EVOLUTION OF THE NORTHERN COCOS PLATE

Previous Work and Observations

The existence of the Cocos plate and its importance to global sea-floor spreading was noted by Morgan (1968), although it was Molnar and Sykes (1969) who first delineated its boundaries. The Cocos plate is bordered on the west by the Pacific plate, on the south by the Nazca plate, and on the east by the North American and Caribbean plates. The first two are divergent plate boundaries and the last is convergent. The relative motion between the Pacific and Cocos plate is nearly east-west at half-rates ranging from 4.5 cm/yr just north of the Orozco fracture zone to 7.4 cm/yr near the equator at the Galapagos triple junction (Hey et al., 1972). The convergent rate between the Cocos and North American plates ranges from 7.9 to 9.0 cm/yr along the middle America trench in the direction of N50°E (Larson and Chase, 1970). The Cocos plate is believed to be a remnant of the old Farallon plate (McKenzie and Morgan, 1969; Atwater, 1970) and originated about 25 m.y. ago when the Galapagos rift zone split the Farallon plate into the Cocos and Nazca plates (Hey, 1975). The precise history of the Cocos plate is complicated somewhat by the evidence of jumps in the spreading center about 4 to 10 m.y. ago (Sclater et al., 1971; Herron, 1972; Anderson and

Davis, 1973). Similar jumps in the spreading center are also apparent on the Nazca plate (Herron, 1972). The fossil ridge crests for the ridge jumps on the Cocos-Pacific boundary are represented by the Mathematician and Clipperton ridges located roughly 600 kilometers west of the present day East Pacific Rise (Anderson and Davis, 1973).

One of the most prominent topographic features on the northern Cocos plate is the northeast-southwest trending aseismic Tehuantepec ridge (Figure 1). Menard (1966) suggested that the Tehuantepec ridge is an arcuate extension of the Siqueiros fracture zone. Such a connection is also implied by the bathymetric contours in the area (Chase et al., 1971). Noting the depth offset across the Tehuantepec ridge, Truchan and Larson (1973) concluded that the ridge is a hinge fault similar to a situation observed at the northern end of the Tonga trench (Isacks et al., 1969). Using two-dimensional gravity models, Woodcock (1975) noted a similar offset in crustal thickness across the Tehuantepec ridge and interpreted it to be a relic fracture zone. This interpretation will be used in the proposed history of the northern Cocos plate.

Magnetic Anomaly Correlation Map

The magnetic data collected by Oregon State University over the northern Cocos plate were combined with an extensive amount of magnetic data gathered by the University of Washington and the Scripps Institution of Oceanography during a seismic refraction survey of the area. Together, the data give excellent coverage over the northern Cocos plate between the Orozco fracture zone and the Tehuantepec ridge. The magnetic anomaly data are shown in Figure 11 plotted along ship tracklines and are of excellent quality. Correlations with known sea-floor spreading anomalies were done using the time scale shown at the bottom of the figure. The time scale is a composite of previously published time scales: 0-3.88 m.y., Cox (1969); 4.01-4.54 m.y., Klitgord et al. (1972); 5.18-8.37 m.y., Talwani et al. (1971); and 8.71-22.69 m.y., Blakely (1974). The theoretical anomaly shown was computed assuming a spreading center striking N10°W at 13°N.

The central anomaly, as delineated by the Brunhes-Matuyama boundary, is easily recognized on all ridge crossings. The small positive anomaly found in the center of all the central anomaly crossings is used to denote the axis of the East Pacific Rise after Rea and Blakely (1975) and is interpreted as a recently emitted pile of new oceanic crust (Sclater and Klitgord, 1973). The ridge crest is offset 95 kilometers in a left lateral sense by the Orozco fracture zone near 15°N, 105°W. There is an abrupt change in the strike of the central anomaly across the fracture zone. North of the Orozco, the central anomaly strikes due north, whereas south of the Orozco its strike is

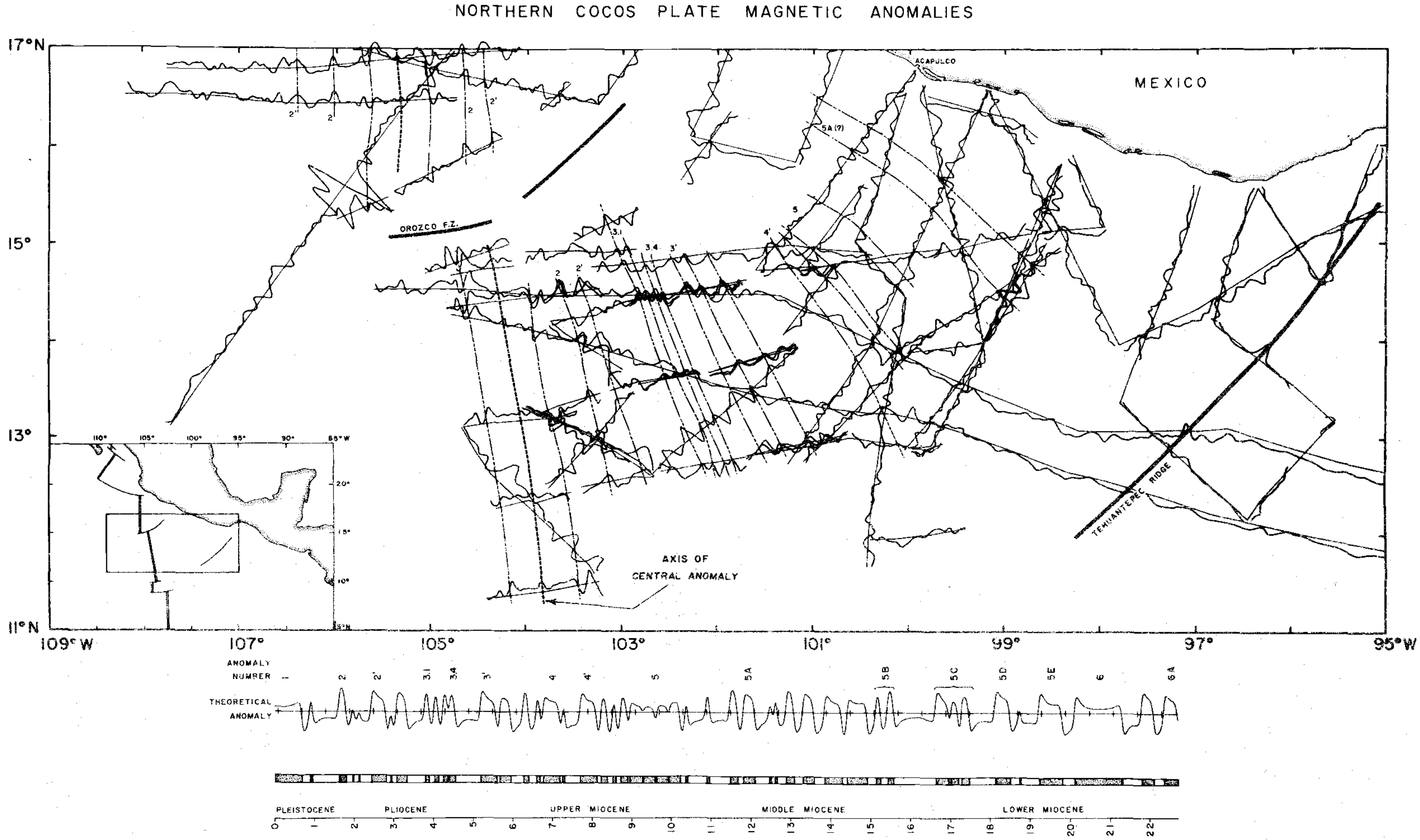

Figure 11. Magnetic anomaly correlation map of the northern Cocos plate. Theoretical anomaly at bottom computed assuming a spreading center oriented N10°W at 13°N.

N10^{o}W. No other apparent offsets can be seen in the central anomaly from the Orozco fracture zone to the southern limits of the data set. We note that the spreading rate, measured using the width of the central anomaly, increases abruptly from 4.5 to 5.0 cm/yr across the Orozco fracture zone.

East of the central anomaly, the Jaramillo anomaly and anomalies 2, 2', 3.1 through 3.4, and 5 are easily identified on several profiles and are correlated with a high degree of confidence. Anomalies 3.1 through 3.4 are particularly convincing correlations. Several other peaks, easily correlated, are also connected but are left unlabeled due to uncertainty in identification.

It is easily seen by the anomaly correlations that the isochrons "fan" away from the East Pacific Rise south of the Orozco fracture zone. For example, the strike of the central anomaly is N10^{o}W, anomaly 3.4 strikes N23^{o}W, and anomly 5 strikes N45^{o}W. This represents an apparent fanning of over 35^{o} in the past 10 million years.

Reconstruction of the Tectonic History of the Northern Cocos Plate

Any tectonic evolutionary scheme must take into account the following observations: 1) the anomalous strike of the eastern extension of the Orozco fracture zone and the subparallel trend of the

Tehuantepec ridge, 2) the present strike of the Orozco and Siqueiros fracture zones within their active portions, 3) the apparent fanning of the magnetic anomalies, 4) the apparent crustal age offset across the Tehuantepec ridge, and 5) the jumps in the spreading centers 4 to 10 m.y. ago. One other fact which cannot be overlooked is the small size of the Cocos plate. In a system of 3 or more plates, the relative poles of rotation between any two plates cannot remain fixed with respect to each other (Le Pichon, 1968; McKenzie and Morgan, 1969). Consequently, the relative motions between plates must change with time. Large plates, such as the Pacific, are probably most stubborn to any changes. Hence small plates such as the Cocos, Juan de Fuca, Caribbean, etc., probably serve as a cushion to absorb the persistent motion of the larger plates (T. van Andel, oral communication). This implies that these smaller plates are no longer acting as internally rigid plates and that the validity of the basic theorems of plate tectonics, when used to evaluate their motions, must be considered with caution.

Before reconstructing the tectonic history of the northern Cocos plate, let us first consider how we might account for the anomalous (i.e., deviating from present Pacific-Cocos motion) strike of the eastern extension of the Orozco fracture zone. In the rigid plate hypothesis, fracture zones must lie along small circles about the relative pole of rotation between the two offset plates. Using the strikes of the Orozco and Siqueiros fracture zones, Molnar and Sykes (1969) determined the location for the Pacific-Cocos pole to be between 20°N, 108°W and 27°N, 114°W. The southerly limit at 20°N, 108°W is extremely close to the Cocos plate, in fact, less than 6° away from the Orozco fracture zone and at first glance appears promising, for its proximity to the Cocos plate may also account for the observed fanning of the magnetic anomalies. A Pacific-Cocos pole so close to the Cocos plate, however, leads to several problems. Observed spreading rates from Figure 1 show a 4.5 cm/yr half-rate just north of the Orozco fracture zone increasing slowly to about 5.2 cm/yr near 11°N. If the above pole were correct, the spreading rate should increase much faster, giving over 7 cm/yr near 11°N. Extrapolated down to the equator, spreading half-rates in excess of 17 cm/yr would be expected which is far from the 7.4 cm/yr rate reported by Hey _et al._ (1972) for this area. Furthermore, recent global models (Chase, 1970; Minster _et al._, 1974) which compute relative motions between plates using information from all plates, yield a Pacific-Cocos pole near 41.3°N, 108.1°W, which is nearly 20° away from the Cocos plate. Small circles about this pole, however, deviate significantly from the eastern trace of the Orozco fracture zone, although within the active portions, the strike of the Orozco and Siqueiros fracture zones appear to lie along small circles about the pole.

The northerly limit for the Pacific-Cocos pole of rotation determined by Molnar and Sykes using fracture zone trends lies close to the Cocos-North American pole at $31.8^{\circ}N$, $123.3^{\circ}W$ (Minster et al., 1974). This suggests that the Orozco fracture zone is a boundary between the Cocos and North American plates. Such a hypothesis is inviting since the Cocos plate segment north of the Orozco is very small compared with other lithospheric plates. In analogy to the Rivera plate to the north (Atwater, 1970), then, we might assume that this plate segment is no longer large or strong enough to continue subduction, and is beginning to lock onto the North American plate.

We can check this hypothesis by examining the seismicity of the northern Cocos plate. Figure 12 shows the seismicity associated with the transform faults which offset the East Pacific Rise. The dense seismicity along the west coast of Central America is caused by the interaction of the Cocos and North American plates. If the plate segment north of the Orozco fracture zone is locking onto North America, then the Orozco must be a ridge-trench transform fault which should be active along its entire length between the East Pacific Rise and the middle America trench. North of the intersection of the Orozco fracture zone with the trench we would also expect a marked decrease in seismicity. Figure 12 shows that these expected features in the seismicity are not observed. Between the East Pacific Rise and the trench, the Orozco fracture zone is inactive with only a few

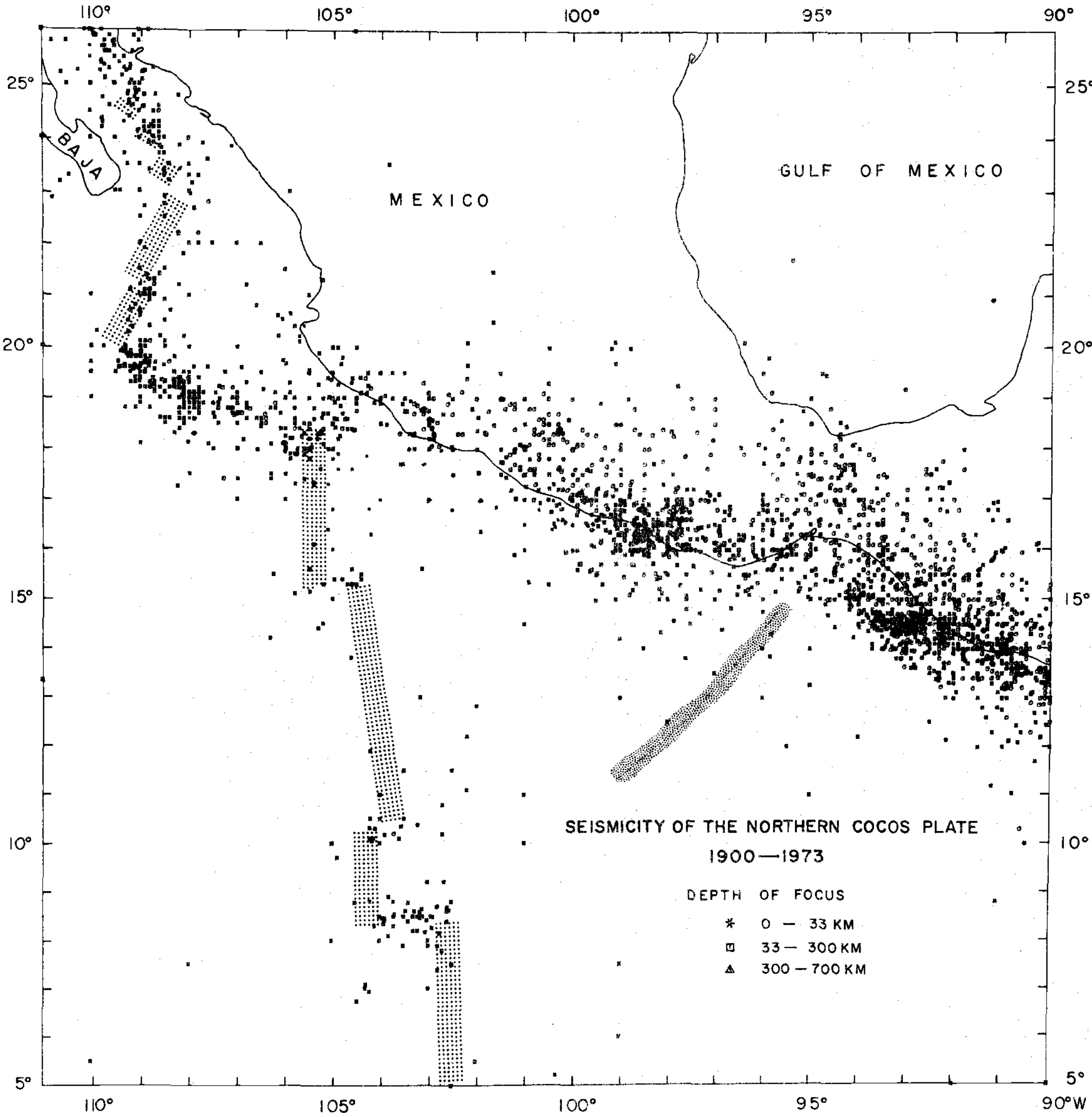

Figure 12. Seismicity of the northern Cocos plate. See Figure 1 for identification of features.

scattered events. There is a slight hint of a decrease in epicenter density along the trench north of its intersection with the Orozco fracture zone, although not nearly enough to consider this plate segment to be locked onto North America. If it is locking onto the North American plate it is, at best, just beginning to do so.

We will now show that all of the observations listed at the beginning of this section can be accounted for by a reconstruction of the tectonic history of the northern Cocos plate. The Cocos plate formed about 25 m. y. ago when the Farallon plate was split apart by the Galapagos rift zone, although the formation of the rift zone was probably not completed until about 15 m. y. ago (Hey, 1975). At about 8 m. y. ago, the situation must have looked similar to that shown in Figure 13a. The relative motion between the Pacific and Cocos plates was in a northeasterly direction as a result of previous Pacific-Farallon motion. The Mathematician and Clipperton ridges were still active spreading centers. The age offset between the Clipperton ridge (segment III) and the ridge segments II and IV in Figure 13a was about 8 m. y. At about 7.5 m. y. ago the spreading axis jumped 220 kilometers eastward from the Clipperton ridge and resumed spreading in crust already 4.5 m. y. old (Anderson and Davis, 1973). At 4 m. y. b. p., the Mathematician ridge ceased to be an active spreading center and also jumped eastward to its present location. Note that both of these jumps had the effect of reducing the

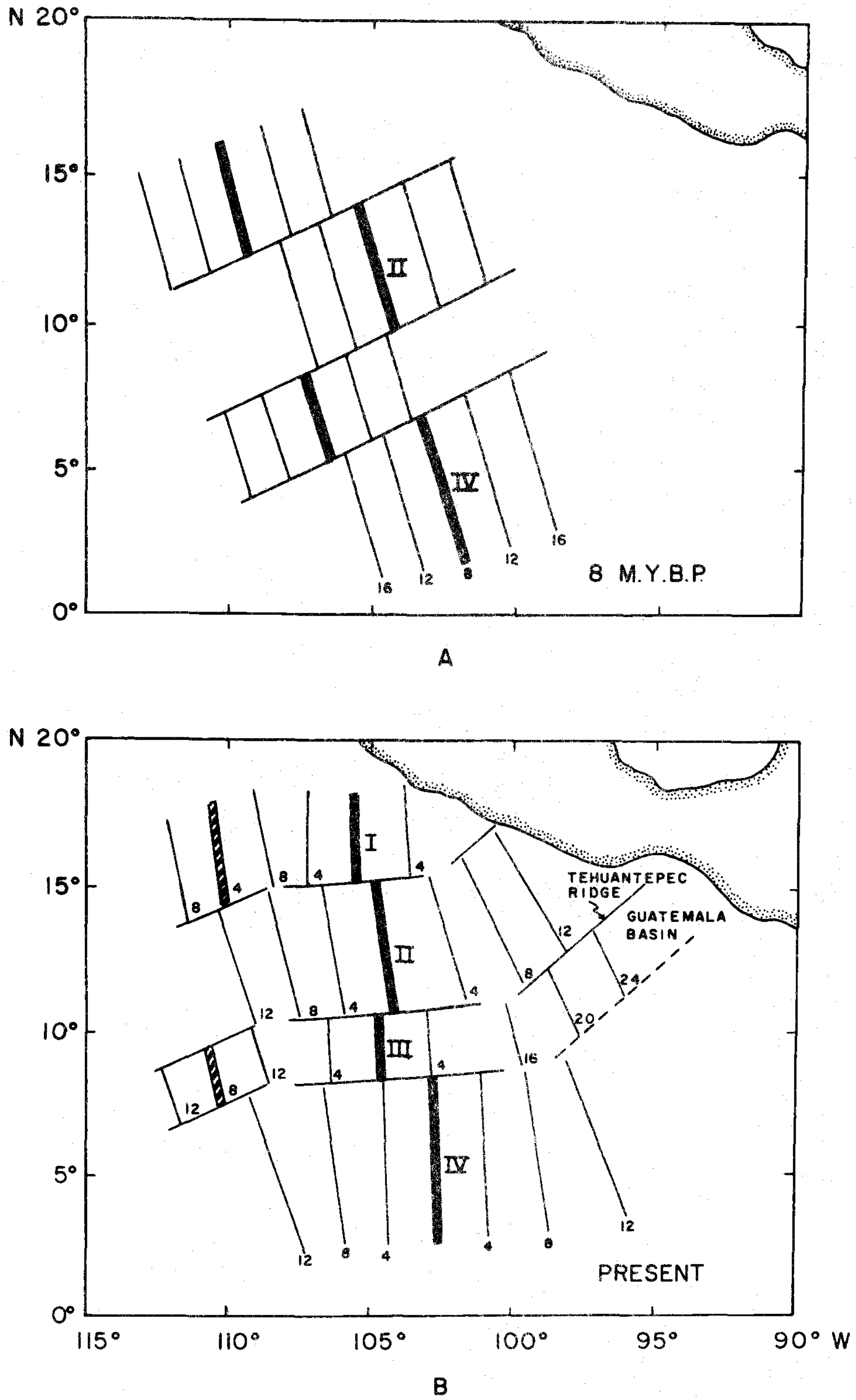

Figure 13. Proposed tectonic history of the northern Cocos plate. Heavy black lines are active spreading centers; striped lines are fossil spreading centers. Reference frame is fixed in a non-rotating system.

fracture zone offsets, bringing the ridge segments more in line with each other. The asymmetric bathymetric profile of the ridge segment in between the two new sections also indicates a trend to straighten the ridge axis. The eastern flank of the rise has a much shallower topographic gradient than the western side indicating asymmetric spreading. The faster spreading rate is to the east so the ridge axis must be migrating westward, the proper direction to reduce the fracture zone offsets. A similar sequence of events eventually eliminated the Surveyor fracture zone in the northeast Pacific (Shih and Molnar, in press) which may indicate that the Orozco and the other fracture zones on the western edge of the Cocos plate will eventually be eliminated also.

Contemporaneous with the jumps in the spreading axes, the Pacific-Cocos pole moved closer to the Cocos plate. It is not clear if this movement was abrupt or gradual, although a reconstruction of the Galapagos rift zone by Hey (1975) supports the latter. The result of the rise crest jumps and the change in relative motion is shown in Figure 13b. The relative motion between the Pacific and Cocos plates is now about N85°E. The former inactive traces of the fracture zones north and south of ridge segment II now form the eastern trace of the Orozco fracture zone and the Tehuantepec ridge. Note that the age offset across the Tehuantepec ridge is in the proper sense (i.e. older crust to the south), whereas previous speculations on the ridge being a continuation of the Siqueiros fracture zone would require an age offset in the opposite sense. The presence of the Guatemala basin, which is a result of older crust, is thus explained by the previous large age offset between ridge segments II and III.

In an effort to align itself towards the changing rotation pole and with the other ridge segments, ridge segment II reoriented by a clockwise rotation of about 20° and has migrated westward to reduce the age offsets across the fracture zones. Recall that the magnetic anomaly map showed a 35° fanning of the isochrons away from the ridge crest. At least 20° of this fanning can thus be explained by the reorientation of the ridge crest in a manner similar to the Zed pattern of Menard and Atwater (1968). The other 15° or so can be easily accounted for by the closer location of the Pacific-Cocos pole. As a result, the isochrons near the trench appear to be nearly parallel with its axis.

The above history is not without its defects. First, the western extension of the fracture zones in Figure 13a are not observed in the bathymetry, although this may be due to inadequate data. A second problem is the lack of bathymetric expression along the southern boundary of the Guatemala Basin similar to the Tehuantepec ridge on the nothern boundary. According to the proposed history, the fossil extension of the Siqueiros fracture zone should form this boundary. Truchan and Larson (1973), however, map the eastern extension of the Siqueiros as running east-west, although there is a hint of northeast trending contours in the bathymetry south of the Guatemala basin.

In spite of these difficulties, the tectonic history of the northern Cocos plate outlined above does account for nearly all of the observed features and provides a working hypothesis from which to expand upon. It is necessary to remind ourselves that we may be pushing beyond the framework of plate tectonics in that the Cocos plate may no longer be acting as rigidly. There is an uncomfortable amount of inner-plate seismic events in Figure 12 to support this conclusion and any further refinements in the above model must take this into account.

CONCLUSIONS

Several of the geophysical observations of the Orozco fracture zone and the surrounding area are easily explained by reconstructing the tectonic history of the northern Cocos plate. These observations include: 1) the anomalous northeast strike of the eastern extension of the Orozco fracture zone and the subparallel trend of the Tehuantepec ridge, 2) the present strike of the Orozco and Siqueiros fracture zones within their active portions, 3) the small age offset across the Orozco fracture zone, 4) the apparent fanning of the magnetic anomalies south of the Orozco fracture zone, and 5) the origin of the Tehuantepec ridge and the apparent age offset observed across it. The proposed tectonic history supposes a change in the Pacific-Cocos pole of rotation about 4 to 7 m.y. ago with a near contemporaneous jump in segments of the spreading axis. The change resulted in a closer pole of rotation which caused the East Pacific Rise (segment II in Figure 13b) to reorient nearly 20° in a clockwise manner.

The Orozco fracture zone has been in existence for at least the past 8 to 10 m.y. and was probably an active offset in the Pacific-Farallon spreading system prior to 25 m.y. ago. There is some strong evidence indicating that the ridge offset across the Orozco fracture zone is shortening, suggesting that it is a transient feature. Most of the offset shortening took place when the ridge axis jumped from the Mathematician ridge east to its present location north of the fracture zone. The asymmetric spreading indicated by the bathymetry and by the different character of the gravity anomalies east and west of the ridge crest south of the Orozco fracture zone (Figure 9) suggest that this ridge segment is migrating westward, in the proper direction to reduce the age offset.

The direction of the jumps in the spreading center and of the migration of ridge segment II in Figure 13b are all consistent with the ridge crest trying to "straighten itself" out. This is undoubtedly of tectonic significance and we speculate that it may be related to the longitudinal flow of material beneath ridge axes proposed by Vogt and Johnson (1975).

Many of the more detailed gravity and bathymetric observations of the Orozco fracture zone are also directly related to the recent tectonic history of the area. The gravity and bathymetric expression of the Orozco fracture zone is relatively subdued in comparison with detailed observations of other fracture zones. This point is emphasized by the lack of a well defined trough only 60 kilometers west of the active portion of the fracture zone. East of the active portion, there are several troughs, all of which have a more northeasterly strike as a result of the reorientation of the Pacific-Cocos pole of rotation. The multiple number of troughs suggests that the fracture zone his migrated along the ridge axis.

Evidence for this migration is also found in the gravity data. A broad, low-density root extending nearly 2 kilometers into the mantle is required to satisfy the observed free-air anomaly over the active part of the fracture zone (profile B-B'). The width of the low-density root is nearly 60 kilometers and is undoubtedly too wide to be accounted for by one fault zone and implies that the fracture zone has not remained stationary with respect to the ridge crest, but has reoriented and/or migrated during its past. Both of these processes have the effect of moving the original shear zone making the low-density root wider.

Several of the observations from the gravity and magnetic data are most likely independent of the particular tectonic history of the northern Cocos plate and we summarize these below. The first of these is the existence of a low-density root under the active portion of the Orozco fracture zone which is probably due to the brecciation and hydrothermal alteration of crustal and upper mantle material (Gumma, 1973). The intense brecciation of material within fracture zones implies that a low-density root should be a ubiquitous feature of all fracture zones, although gravity profiles across the Romanche fracture zone by Cochran (1973) and across the Panama fracture zone by Barday (1974) indicate that this is not the case.

On all of the two-dimensional models designed to fit the observed gravity across the Orozco fracture zone, a thinning of oceanic layer 2 is required near the troughs in order to accommodate the short wavelength anomalies. Because of the wide trackline spacing we cannot rule out three-dimensional structure as the cause of the short wavelength anomalies. However, similar observations on gravity models across the Rivera fracture zone and the fact that rocks proposed to be from the lower oceanic crust have been dredged from fracture zones implies that much of the thinning is real. We would also expect that this layer would be thinned somewhat by brecciation within the fracture zone.

Over the East Pacific Rise, both north and south of the Orozco fracture zone, there is a 5 to 10 mgal peak superimposed upon a somewhat flat anomaly. Such a peak is consistent with the upwelling of convective currents proposed under ridge crests (Kaula, 1972). In two models constructed to account for the ridge crest anomalies, both required a thickening of layer 2 by approximately 0.5 kilometers and thinning of layer 3 by about 2 kilometers. The latter observation appears consistent with previous ridge crest models across the East Pacific Rise (e.g Talwani, 1965; Lu, 1971) and seismic refraction studies on the thickness of oceanic layer 3 with age (e.g. Christensen and Salisbury, 1975).

A 100 to 200 gamma positive anomaly is located over the main trough of the Orozco fracture zone. Although several explanations have been proposed for similar peaks over other fracture zones, we feel that the anomaly is small enough to be accounted for by topography and the remanent magnetization of the oceanic crust as suggested by Gumma (1973).

Lastly, we note the presence of a large amplitude anomaly (over 1300 gammas) located at the intersection of the Orozco fracture zone and the northern extension of the East Pacific Rise. Since this anomaly is located nearly 35 kilometers away from any substantial bathymetric relief implies that the anomaly is not a topographic effect. Using the interpretations of a nearly identical situation observed at the intersection of the Juan de Fuca ridge and Blanco fracture zone in the northeast Pacific, we conclude that the anomaly is caused by an accumulation of magnetic material which has possibly "leaked" out of the ridge into the Orozco fracture zone. In light of the proposed longitudinal flow of magma beneath ridge crests (Vogt and Johnson, 1975), it is not unlikely to expect such a leakage to occur.

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