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Title: STRUCTURES OF THE CONTINENTAL MARGIN OF CENTRAL AMERICA FROM NORTHERN NICARAGUA TO NORTHERN PANAMA

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Gravity and seismic data obtained by the geophysical group at Oregon State University on the R/V YAQUINA during 1969, 1971, and 1973 plus other available data over the area just west of Nicaragua and Costa Rica indicate the tectonic complexity of the region. Gravity measurements show negative free-air anomalies over the Middle America Trench and the continental shelf of Nicaragua with values as low as -120 mgal and -90 mgal respectively. An outer shelf gravity high of +35 mgal occurs between the lows. A large positive anomaly attaining values as high as +110 mgal is associated with the Nicoya Complex, a late Mesozoic assemblage, on the Nicoya Peninsula, Costa Rica. Continuous seismic reflection records acquired along the continental shelf of Nicaragua and Costa Rica indicate a large sediment-filled basin off the coast of Nicaragua coincident with the large negative gravity anomaly on the shelf. Free-air gravity anomalies and seismic

reflection profiles suggest an offshore continuation of the Nicoya Complex. Two crustal and subcrustal cross sections of the continental margin of Nicaragua show a large anticlinal structure near the surface of the outer shelf. This structure and an underlying layer are postulated to be marine sediments and basalts similar to those of the Nicoya Complex. The cross sections suggest a ruptured oceanic layer beneath the trench.

Imbricate thrusting of oceanic crust along the continental slope is postulated as the mechanism of formation of the continental slope and shelf, and hence the Nicoya Complex of Costa Rica. This model has to be modified for southern Costa Rica where the Cocos Ridge terminates the Middle America Trench. The present elevation of the Nicoya Complex onshore may be attributed to imbricate thrusting and concurrent uplift of the shelf by the Cocos Ridge during subduction.

Structures of the Continental Margin of Central America from Northern Nicaragua to Northern Panama

by

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TABLE OF CONTENTS

LIST OF FIGURES

STRUCTURES OF THE CONTINENTAL MARGIN OF CENTRAL AMERICA FROM NORTHERN NICARAGUA TO NORTHERN PANAMA

INTRODUCTION

The continental margin of Central America from northern Nicaragua to northern Panama provides an intriguing area for study. The work of Minster *et al.* (1974) indicates that the direction of motion of the Cocos plate with respect to the North American plate is approximately N37° E with a rate of convergence of about 10 cm/yr at 11°N, 86°W. Off the coast of southern Costa Rica the Middle America Trench terminates at the Cocos Ridge. The presence of the Nicoya Complex, uplifted marine sediments and pillow basalts, on the Nicoya Peninsula of northern Costa Rica further complicates the tectonic picture of the area. Seely *et al.* (1974) suggest that this rock assemblage occurs beneath the shelves of Nicaragua, El Salvador, and Guatemala. Inland from the coasts of Nicaragua and Costa Rica are prominent northwest-southeast striking faults, such as the boundary faults of the Nicaraguan Depression.

Geophysical data collected by the Geophysical Group of Oregon State University (OSU) aboard the R/V YAQUINA in 1969, 1971, and 1973 was used to investigate the offshore geologic structures. A free-air gravity anomaly map made from gravity data collected by OSU, The Hawaii Institute of Geophysics (HIG), and the National Oceanographic and Atmospheric Administration (NOAA) illustrates structural trends in the region along the coasts of Nicaragua, Costa Rica, and northern Panama. Seismic reflection records of the continental shelf of Nicaragua and Costa Rica identify some of the structures suggested by the free-air gravity anomalies. Two cross sections constrained by gravity and magnetic data were constructed to determine the crustal and subcrustal structures of the continental margin of northern Nicaragua.

By combining marine geophysical data with the land geology of Nicaragua and Costa Rica, this study interprets the structures of the continental margin of this area, and postulates an origin for these structures, including the unusual Nicoya Complex.

PREVIOUS WORK

The continental margin of Central America has received considerable attention from geophysicists in the last 25 years. Most of the work, relative to this study and summarized below, is reported in general regional studies. However, much of the geological and geophysical information available on the Cocos Ridge comes from detailed surveys of the ridge and the adjoining Panama Basin, and McBirney and Williams (1965) and Dengo (1962) report geologic studies of Nicaragua and Costa Rica. The work done in the thesis area can be divided into three areas: (1) the continental margin of Nicaragua and Costa Rica, (2) the Cocos Ridge and the northwestern portion of the Panama Basin, and (3) Nicaragua and Costa Rica.

Nicaragua, Costa Rica: Marine Geophysical Studies

Bathymetry

Agassiz (1892), used a 100 fathom line to define the shelf boundary and described the continental shelf from Costa Rica to Tehuantepec, Mexico, as narrow. The 100, 500, and 1000 fathom lines indicated a steep continental slope in the same area. The lower slope, between the 1000 and 2000 fathom lines, is less steep between Costa Rica and Tehuantepec than the slope north of Tehuantepec.

Heacock and Worzel (1955) renamed the Guatemala Trench, the Middle America Trench. Using data collected by the USS Chopper in 1949, they noted that the trench extends from 10°N, 86°W to 29°N, 106°W. They reported a 30-60 mile wide continental shelf south of the Gulf of Tehuantepec. The gradient of the continental slope ranges between 3° and 6°, compared to the 1° to 3° gradient of the seaward wall of the trench. They noted that the Cocos Ridge terminates the trench and that the Guatemala Basin extends approximately 500 miles north of the ridge at a depth of 2000-2200 fathoms.

In 1961, Fisher published echo soundings collected by the Scripps Institution of Oceanography (SIO) from 1952-1959. He described a wide shelf off the Coasts of Nicaragua and northern Costa Rica. The continental slope, ranging in inclination from 4° to 8°, exhibits numerous submarine canyons, particularly off Puntarenas, Costa Rica. The trench, whose axis is v-shaped, widens off Costa Rica before shoalling near the Cocos Ridge. The small amount of sediment fill in the trench axis off Nicaragua may be, in part, a result of the wide shelf trapping most of the terrigenous sediment. The seaward wall of the trench has a slope of 2° to 6°. The ocean floor west of Costa Rica is smooth and approximately 1700-1800 fathoms deep, except where groups of seamounts occur southwest of the Nicoya Peninsula.

Chase (1968) utilized data collected in the previous 15 years by various governmental agencies and academic institutions in the construction of his bathymetric maps. His map of the area west of Nicaragua and Costa Rica shows the Middle America Trench to be deepest off central Nicaragua, where the depth is greater than 2800 fathoms.

In 1971, SIO prepared new bathymetric maps that were subsequently published by the U. S. Naval Oceanographic office. Figure 1 shows a combination of two maps that encompasses the area west of Nicaragua and Costa Rica.

Seismic Reflection and Refraction Studies

In 1954, SIO shot refraction line (STA-7) in the trench axis near La Union, El Salvador (Shor and Fisher, 1961). This refraction station is the southernmost of five similar stations. This study uses the results of STA-7 to constrain model crustal sections of the continental margin of northern Nicaragua. The refraction data collected at this southernmost station shows relatively thick oceanic crust beneath the trench (Shor and Fisher, 1961). The depth to the mantle is 15.97 km in the vicinity of the trench, and no layer two (transition layer) was detected at this location.

Reflection profiles of the Middle America Trench off northern Nicaragua and central Costa Rica show a sediment covered bench on

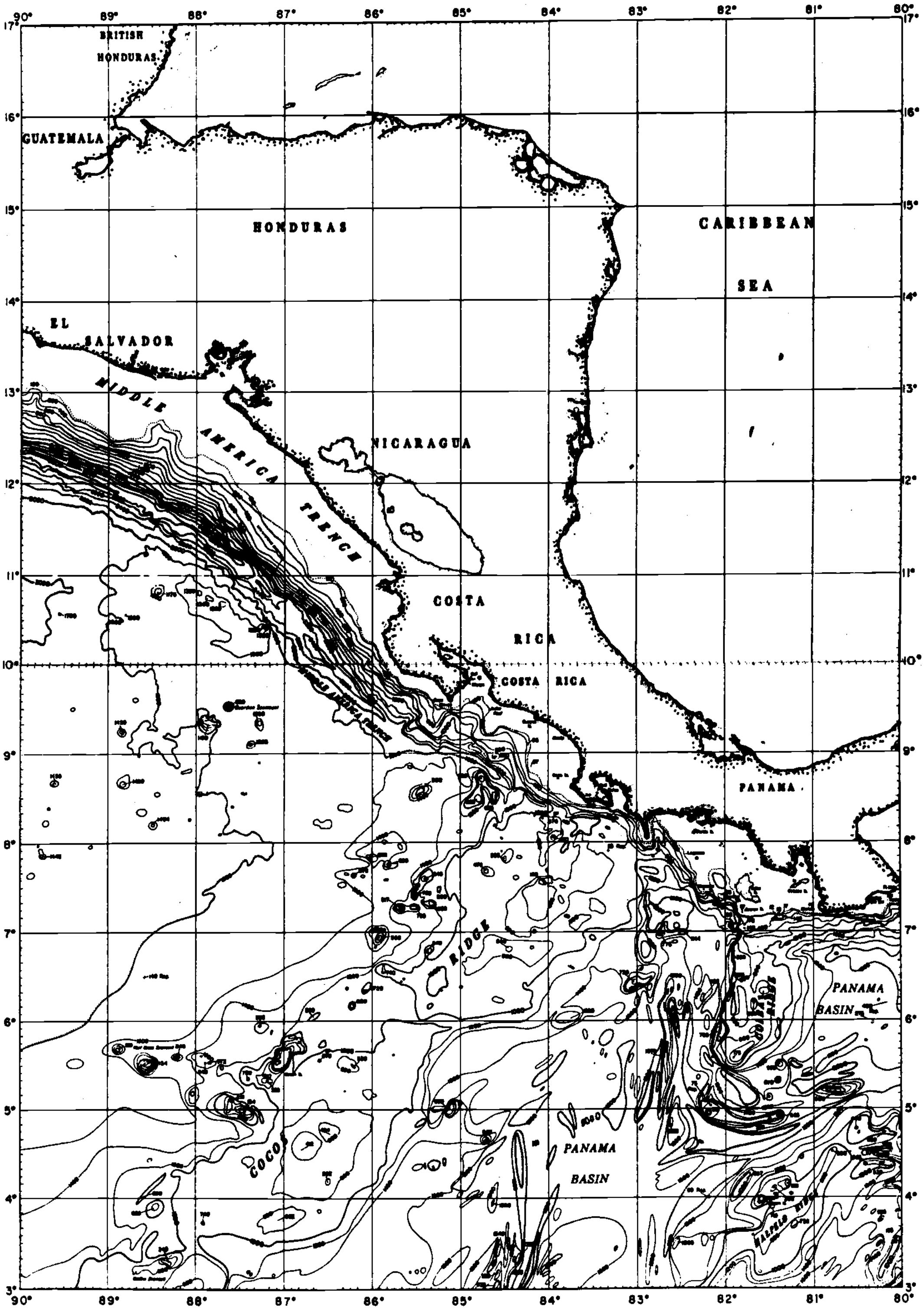

Figure 1. Bathymetric map of the continental margin from northern Nicaragua to northern Panama. Contour interval is 200 fathoms. The 100 fathom contour is included. (USNOO Bathymetric atlas of the northeastern Pacific Ocean, 1971).

the continental slope at water depths of 1.0 and 1.7 km respectively. In the Nicaraguan profile (SIO1, Figure 2) very little to no sediment cover is observed on the continental slope near the trench bottom. Also, the records indicate an absence of sediment in the trench axis. This is in contrast with the profile off Costa Rica (SIO 2, Figure 2) which shows slumped sediments on the continental slope near the trench axis and 0.5 km of sediment in the trench bottom. The folded sediment on the seaward wall of the trench has a thickness of up to 0.6 km. Further, seaward of the trench, seamounts rise above 0.55 km of sediment. Also, a strong acoustic horizon divides the sediment into two layers, with the upper layer being less disturbed than the lower layer.

Earthquake Studies

Molnar and Sykes (1969) investigated the seismicity of the Central America area and showed that the majority of the earthquakes of the area occurred along the boundaries of the Cocos plate. The center of the plate is relatively aseismic. Focal mechanisms, determined for the earthquakes occurring along the continental margin of Nicaragua and Costa Rica, indicate that the Cocos plate underthrusts Central America. The direction of the relative motion between the Cocos plate and Central America is about N30° E (Molnar and Sykes, 1969).

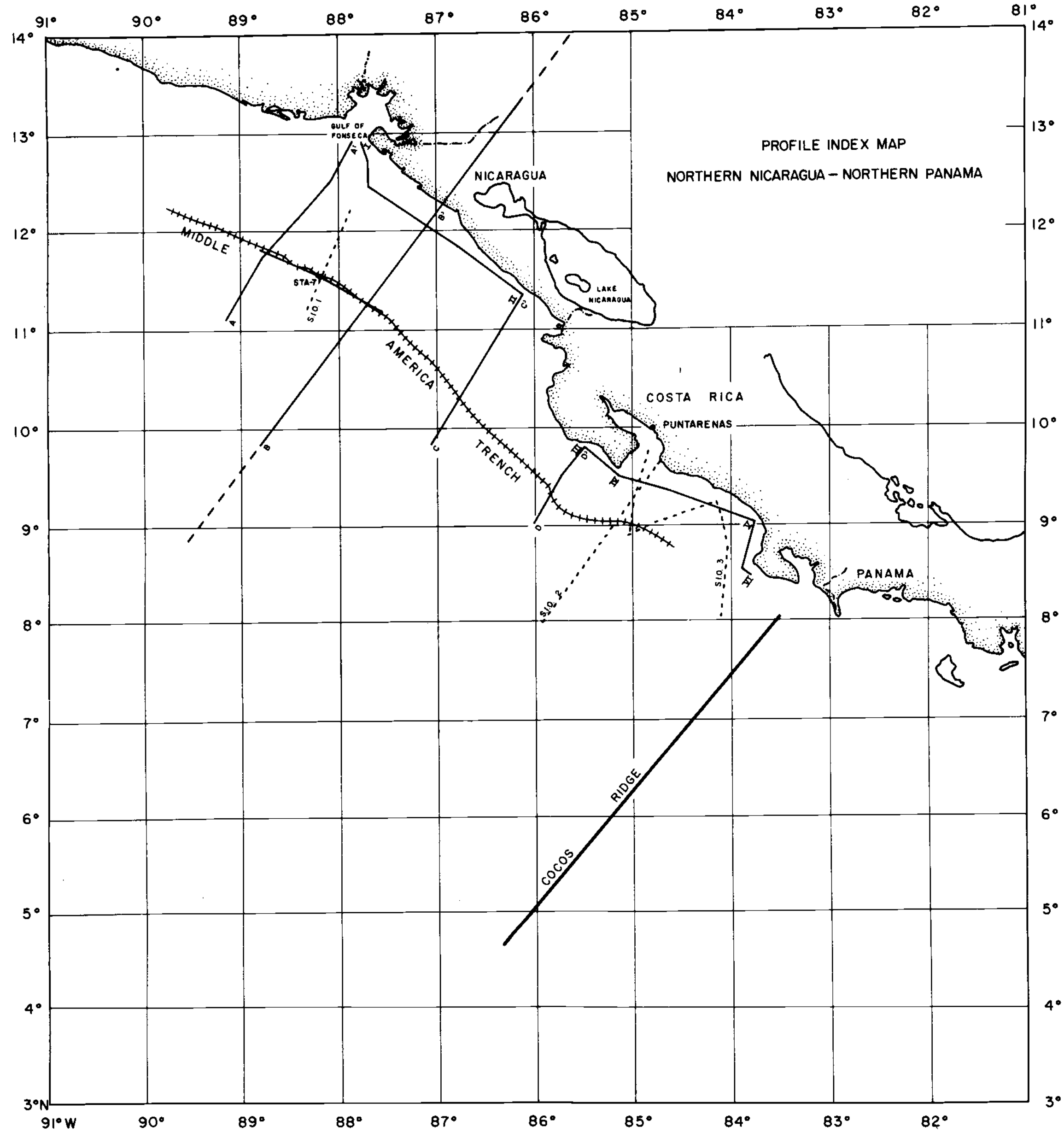

Figure 2. Index map showing location of seismic reflection profiles A-A', C-C', D-D', I-II, III-IV-V-VI, SIO1, SIO2 and SIO3, crustal and subcrustal cross section B-B', and seismic refraction station, STA-7.

In an effort to find a method for predicting the locations of impending large shallow earthquakes, Kelleher, et al. (1973) mapped the epicenters and rupture zones of large earthquakes that occurred along the Middle America Arc during the last century. They found that there is an approximate time interval of 50 years between the occurrences of large earthquakes for this area. Also, gaps exist in the seismicity where no large earthquakes have been detected for at least 45 years. Three such gaps occur along the coasts of Nicaragua and Costa Rica.

Carr et al. (1974) conducted a similar study in which they divided the Middle America arc into segments based upon volcanic lineaments. Again, Nicaragua and Costa Rica are divided into three segments. These segments coincided fairly well with peaks in a smoothed curve found by graphing the energy released by shallow earthquakes in Central America versus distance along the coast. According to Carr, et al. (1974), these segments reflect discontinuities in the subduction of the lithospheric slab. The stresses for each segment may be different such that the plate is underthrusting at a different strike and dip when compared to its neighboring segment. This variation in subduction determines the deep seismic zone and the location of the volcanic chain for each segment. "Deep crustal faults" mark the segment boundaries and extend inland as far as the line of volcanoes (Carr et al., 1974).

Kelleher (1975) attempts to explain segmentation of the continental margin as a response to changes in the subduction process due to the varying buoyancy (density) of the plate. He suggests that a particularly buoyant section, such as a ridge with its crustal root, may resist subduction at the trench, which in turn may result in a shift in volcanic lineaments, a gap in seismic activity, or a change in any of the other tectonic evidences of subduction.

Heat Flow

Von Herzen and Uyeda (1963) reported low heat flow values in the Guatemala Basin. Data collected on the Vema cruises, 18 and 19, (Langseth *et al.*, 1965) confirmed this anomalous heat flow, and indicated that the area did not include the Tehunatepec and Cocos Ridges. Even though the Guatemala Basin exhibits low heat flow of approximately 0.84 $\mu cal/cm^2/sec$, there seems to be no appreciable decrease in heat flow near the bottom of the Middle America Trench, as would be expected if thermal convection were responsible for the variations in heat flow values (Vacquier *et al.*, 1967).

Gravity

Vening Meinesz (1960) interpreted pendulum gravity measurements collected by personnel aboard the submarine, "Walrus" in the Pacific Ocean (Figure 4). The gravity profile transverse to the coast of Costa Rica at Puntarenas suggested no significant gravity trends.

Worzel (1965) also, published pendulum gravity measurements collected off the coasts of Nicaragua and Costa Rica (Figure 4), but presented the data without interpretation.

Magnetics

Even though the Continental margin of Central America has been the site of many geophysical studies, there has been little magnetic work reported in the area off Nicaragua and Costa Rica. Herron (1972) presents a map of magnetic age for the East Pacific Rise, but the anomaly pattern does not extend to the coasts of Nicaragua and Costa Rica. Hence, the magnetic history of this area is unknown.

Terrestrial Geological and Geophysical Studies

Geology of Nicaragua

McBirney and Williams (1965) investigated the tectonic significance of the volcanic units of Nicaragua and the relationship between these units and the Nicaraguan Depression. They divided Nicaragua into four provinces based on geology and physiography: the Pacific Coastal Plain, the Nicaraguan Depression, the Interior Highlands, and the Atlantic Coastal Plain (Figure 3). The geology of Nicaragua as shown in Figure 6 is a generalized version of their map, and the

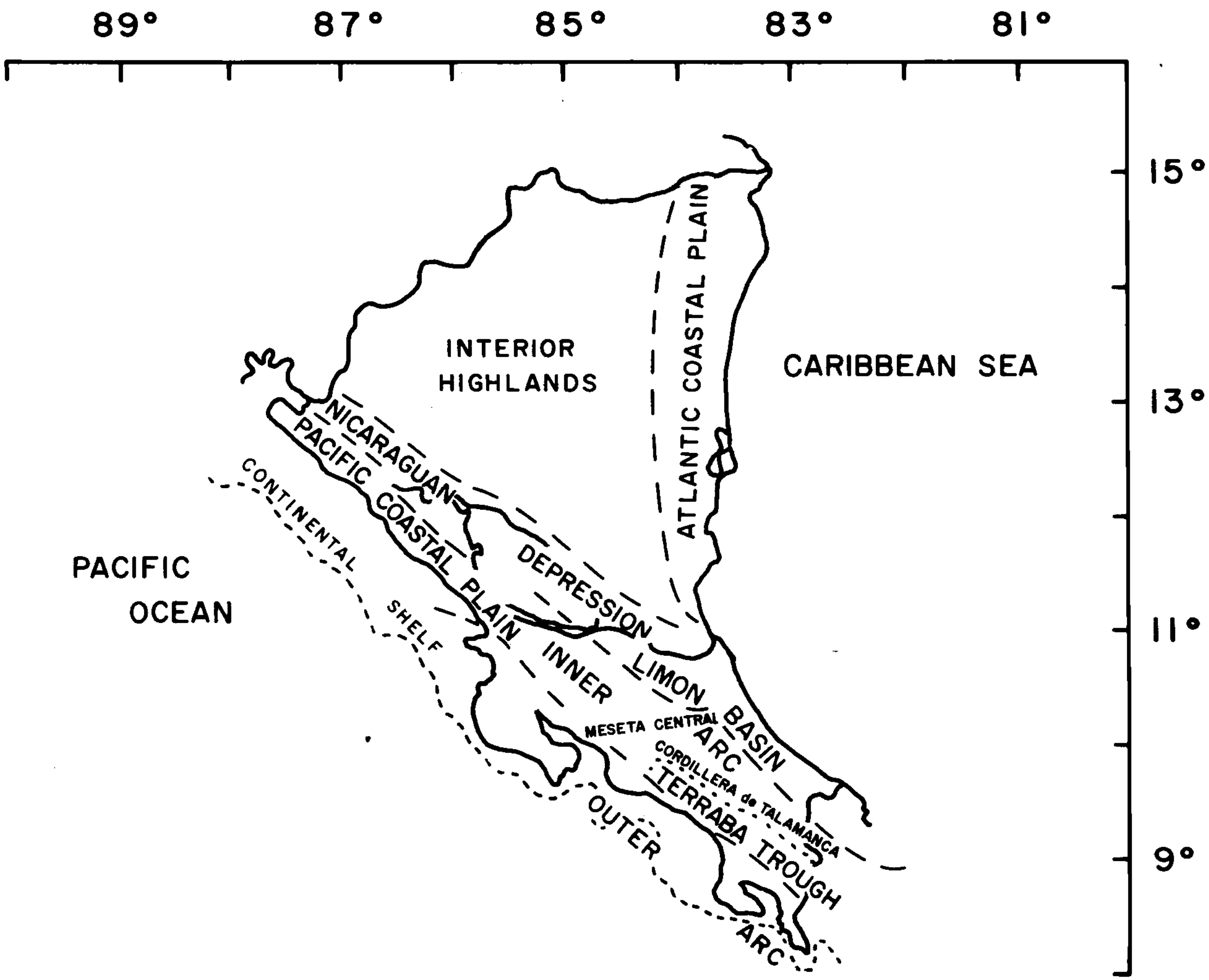

Figure 3. Geographic and structural province map of Nicaragua and Costa Rica (land geology after McBirney and Williams, 1965; Dengo, 1962). The dashed line that represents the outer margin of the continental shelf follows the 100 fathom contour shown in Figure 1.

following discussion is a summary of their study.

The Pacific Coastal Plain is a narrow province extending along the coast of Nicaragua from El Salvador to Costa Rica. A thick Late Cretaceous and Cenozoic sedimentary sequence covers the southern portion of this coastal province. This sequence is composed of tuffaceous sediments and may rest upon the "Nicoya Complex," a sequence of Cretaceous marine sediments and basalts found mainly on the Nicoya Peninsula of Costa Rica. This tuffaceous, marine sedimentary sequence is over 10 km thick and forms an anticline that plunges to the northwest along the Pacific Coastal Plain. Rocks of all ages from Late Cretaceous to Miocene age are present without significant interuption of deposition. The Miocene and older sediments are folded and faulted. The deposition of Pliocene marine sediments (the El Salto Formation) occurred when the Pacific Coastal Plain was submerged for a short period of time after the deformation of the earlier sediments. Because the El Salto Formation is horizontal, there is a sharp unconformity between it and the miocene deposit (El Fraie Formation). Samples from the entire sequence indicate that the oldest sediments have been metamorphosed. Also, dikes and sills have intruded the sediments in many places. The geologic map (Figure 6) shows the many Tertiary sediments as one unit. To the northwest the Miocene sediments grade into a contemporaneous series of ignimbrites, lavas, and volcanic sediments.

This volcanic series, the Tamarindo Formation, is approximately 80 km in length, extends as far north as Leon, and is exposed in northwest-striking ridges. Volcanic rocks laid in a swampy or deltaic type environment occur near the El Fraie-Tarmarindo contact, but disappear to the north where only landlaid volcanic rocks occur. Quaternary volcanic rocks occur along the southern margin of the Gulf of Fonseca where there is an isolated volcano. The major chain of Quaternary volcanoes occurs along the eastern boundary of the Pacific Coastal Plain.

The scarps of the Mateare Fault and another unnamed northwest trending fault respectively form the western and eastern boundaries of the Nicaraguan Depression, a graben filled with over 1 km of Quaternary sediment. This boundary faulting and sediment deformation in the Pacific Coastal Plain are contemporary and of Mio-Pliocene age. The Mateare Fault Scarp extends for 70 km south and west of Lake Managua. North of Lake Managua the fault is hidden beneath alluvium and volcanic sediments. The crest of the Mateare Scarp is almost 1 km above the graben floor. During the formation of the scarp the coastal plain was tilted seaward. The tilting is recent, with movement continuing to the present, as indicated by the erosion of volcanic sediments and seismic activity on the Mateare scarp. The fault system that forms the northeastern boundary is more prominent because it extends from the Gulf of Fonseca to the southeastern border of Nicaragua. The faults are "characterized by hinge movements" and the depression is tilted to the southwest. Normal faulting is less prominent than on the southwest side. The alluvium in the graben thins near the northeastern boundary where volcanic hills rise above the sediment, which indicates that the graben subsided most in the southwest.

Fault systems that are less prominent than the boundary faults complicate the tectonic history of the Nicaraguan Depression. One of these fault systems offsets the main axis of the Quaternary volcanoes and the Mateare Fault Scarp toward the coast (Figure 6). Vents and tension fractures of individual Quaternary volcanoes appear aligned north-south. In addition, N-S trending faults occur northeast of the depression that seem to be younger than more dominent northeast faulting. An example of the northeast faults is near the northeastern corner of Lake Nicaragua where faults transect a series of fault blocks. The north-south striking, right-lateral faults may be related to Quaternary tectonics in western Nicaragua. The faulting on northeast trends is thought to be contemporaneous with the folding of the Rivas formation in the southern portion of the Pacific Coastal Plain.

The Interior Highlands lie to the east of the Nicaraguan Depression. This province consists of undifferentiated Tertiary volcanic rocks.

Geology of Costa Rica

Hill (1898) described the geology from Puntarenas to Port Limon and included a description of the Nicoya Peninsula. He reported the presence of silicates and greenish quartzite on the peninsula. Hill noted that the green quartzite may be a "remnant of the oldest rocks exposed in Costa Rica." Romanes (1911) investigated the area from San Jose to the Gulf of Nicoya. Near the Gulf of Nicoya along the Avangares River (north of Puntarenas) he found an outcropping of dark, basic, igneous rock which he called limburgite. The rock contained serpentine, fresh olivine, rhombic pyroxine, and serpentinized olivine. Dengo (1962) interpreted the outcropping as either a basic member or a differentiate of intruded Nicoya Complex in his study of the relationship between the igneous rocks of Costa Rica and tectonic events. The following discussion is a summary of his work.

Structurally, Costa Rica can be dividied into three provinces (Figure 3). The outer arc encompasses the peninsulas along the Pacific coast. Northwest-southeast trending faults form a boundary between the outer and inner arcs. The inner arc is the main structural province and is subdivided into the Cordillera de Talamanca and the Terraba Trough. The Cordillera de Talamanca has a northwest trend and extends southward into Panama. It is separated from the volcanic ranges to the north by the Meseta Central and the

Terraba Trough by "subparallel northwest-southeast trending faults, downthrown on the trough side." The La Faralla Fault divides the Terraba Trough from the outer arc. The Limon Basin borders the inner arc on the northeast and east. The basin is a sediment-filled geosyncline.

The Nicoya Complex is the oldest rock formation in Costa Rica and occurs in the outer arc (Figures 3 and 6). The complex is composed of sedimentary rocks--dark graywackes, cherts, siliceous aphanitic limestones--and igneous rocks--basalt agglomerates and flows with intrusions of diabase, gabbro, and peridotite in the form of sills and dikes. The complex forms a major portion of the Nicoya Peninsula, but also occurs on the Herradura, Osa, and Burica Peninsulas. Pillow basalts also occur on the Nicoya Peninsula as well as on the Herradura and Burica Peninsulas. At one place on the Nicoya Peninsula, the diameters of the pillows are from 50 cm to 1 m. The age of the Nicoya Complex is uncertain but is older than upper Cretaceous and possibly as old as Jurassic.

Because there is no geophysical evidence of "true continental crust" on the Caribbean side of Costa Rica, Dengo (1962) concluded that at the time of the formation of the Nicoya Complex, there was no continental rock exposed near it. Dengo also makes the assumption that a volcanic island arc was present along the outer arc. Hence, this volcanism provided the lavas, graywackes, conglomerates, and the conditions necessary for the "sedimentation of the cherts and aphanitic limestones," with the "geosynclinal Cretaceous sediments" being deposited later (Dengo, 1962).

Serpentinized peridotite occurs on the Santa Elena peninsula. The peridotite was probably emplaced at the time the Nicoya Complex was being deformed. The mountains on the peninsula strike east-west and line up with the Clipperton Fracture Zone (Menard, 1955; Dengo, 1962).

The Cordillera de Talamanca is comprised of early Tertiary volcanic rocks, granitic intrusions, and basalt dikes. Upper Tertiary volcanic rocks are present in the northwestern portion of the inner arc, the Terraba Trough, and Limon Basin. An andesitic sequence is associated with the northwestern inner arc while "water-laid pyroclastic rocks with associated agglomerates and lava flows" are characteristic of the volcanic rocks in the Terraba Trough.

The Terraba Trough and the Limon Basin also contain marine sediments that range in age from Eocene to Miocene. The sediments in the Limon Basin are thicker due to the synclinal folding of the basin.

Quaternary volcanic rocks occur along the northwestern portion of the inner arc and in the Meseta Central--a depression trending east-west, just south of the volcanic ranges.

Geophysical Information

Woollard and Rose (1963) listed the gravity values for their standard base stations in Central America, a part of a world-wide network. The Woods Hole-University of Wisconsin gravity program, with the aid of the California Exploration Company and the cooperation from the Instituto de Geografia of Costa Rica and the Inter-American Geodetic Survey, collected gravity measurements and established base stations at airports and along railway and highway systems. This joint effort was started in 1949 and still continues.

Monges Calderas (1961; Henningsen and Weyl, 1967) presented a map of Bouguer gravity anomalies of Costa Rica. A gravity high of +100 mgal over the Nicoya Peninsula, and gravity lows of -50 mgal and -70 mgal near San Jose and the borders of Costa Rica and Panama respectively are prominent.

The Geology of Western Nicaragua (a natural resources inventory project, 1972) contains a compilation of pre-existing geophysical data for Nicaragua. Results of the project include a map of the observed magnetic field and several profiles resulting from an aeromagnetic survey of much of the Pacific Coastal Plain. The magnetic measurements indicate a magnetic "basement," thought to be of early Cretaceous age, in the southwestern part of the Pacific Coastal Plain. Off the coast of southwestern Nicaragua the magnetic basement occurs at a maximum depth of 5.8 km below sea level.

Carr et al. (1974) refer to left-lateral strike-slip motions near Managua (described by Brown et al., 1973) in their paper on the segmentation of continental margins. They suggest that the north-south trending volcanic chain coincides with E-W tensile stresses that are compatible with the observed left-lateral motion of faults oriented N30°-40°E.

Studies of the Cocos Ridge and Northwestern Panama Basin

Many of the early studies of the Cocos Ridge actually dealt with Cocos Island (Figure 1), the only portion of the Cocos Ridge rising above the ocean surface. It is located at 5°32' N. latitude, 87°2'W. longitude, and is of volcanic origin (Chubb, 1933). Shumway (1954) described the topography of the Cocos Ridge and considered the idea that the ridge was once above water. Other investigations of importance to this study include pendulum gravity measurements across the ridge by Vening Meinesz (1960) and a bathymetric map of the Panama Basin, prepared by SIO data (Naval Oceanographic Office, 1971) which includes the Cocos Ridge (Figure 1).

Geological and geophysical studies in the Panama Basin - the area offshore Panama and bordered by the Cocos and Carnegie Ridges - resulted in a paper by van Andel et al. (1971) in which they discuss the tectonics of this complex area. Their study is based on geophysical data collected by SIO, OSU, and Lamont-Doherty Geological Observatory. They noted that the Cocos Ridge appears to be segmented by both north-south and east-west faulting. Van Andel, et al. (1971) describe the faults as growth faults, which exhibit only a small amount of seismic activity. Two fracture zones, well defined to the east of the ridge, are the Coiba Fracture Zone and a system of faults near 85°W. longitude. Part of the Coiba Fracture Zone forms the eastern boundary of the Cocos Ridge at its landward end and the fracture zone at 85°W. longitude cuts across the ridge crest. Van Andel et al. (1971) suggested that left-lateral motion along the north-south faults is responsible for the irregular outline of the ridge, and that increasing offset to the east suggests transcurrent faulting.

Van Andel et al. (1971) postulated that the Cocos Ridge was once a part of an ancestral Carnegie Ridge. Malfait and Dinkelman (1972) presented a pictorial representation of this hypothesis of the origin of the Cocos Ridge in their proposed evolution of the Caribbean plate. Their diagram (Figure 6, p. 260) shows the Cocos Ridge entering the Middle America Trench in the Late Pliocene.

Barday (1974) used gravity data to construct crustal and sub-crustal models of structures of the Panama Basin. He reported an average free-air gravity anomaly of over +20 mgal for the Cocos Ridge, and anomalies over +40 mgal at the landward end of the ridge.

Barday suggested that these latter positive free-air anomalies indicate that the landward end is uplifted due to a bending of the lithosphere, a consequence of subduction. He noted that the water depths over the fracture zones are less than those of the surrounding area, but the Moho is deeper, except at the northern portion of the Panama Fracture Zone (referred to as the Coiba Fracture Zone by van Andel et al., 1971) between the Cocos and Coiba ridges. The Moho shoals beneath the graben associated with the northern section of the Panama Fracture Zone.

Barday (1974) suggests that the Cocos Ridge was formed by the Cocos plate passing over the Galapagos hotspot. This formation of the Cocos Ridge is preferred by Hey (1975) over the ancestral ridge hypothesis. In Hey's tectonic reconstruction of the Galapagoes area, the northeastern end of the Cocos Ridge reached the Middle America Trench between 10 and 15 mybp.

NEW DATA

Personnel of the OSU geophysical group collected much of the data used for this study. During cruises in 1969, 1971, and 1973 bathymetric, seismic reflection, magnetic, and gravity measurements were made off the coasts of Nicaragua, Costa Rica, and Panama.

A 12 kHz acoustic signal, reflected from the sea floor and recorded on a single-channel EPC graphic recorder at a four second sweep, provided bathymetric information. OSU personnel digitized the analog bathymetric records and Matthews' velocity tables (1939) provided the means to convert uncorrected fathoms to corrected meters.

A seismic reflection system recorded a reflected seismic signal that originated from two 40 cu. in. air guns. The reflected signals, detected by a hydrophone streamer and recorded on a single-channel EPC graphic recorder at a four second sweep rate, were interpreted in analog form.

A proton precession magnetometer towed behind the ship yielded marine magnetic data. The digitization interval of the analog records was five minutes, except where the data required shorter sampling intervals. The data was then reduced to anomaly form by the removal of the theoretical field given by the International Geomagnetic Reference Field (IGRF, 1967). The IGRF yielded an incorrect regional field for the 1971 magnetic data used in the crustal and subcrustal cross sections. Subsequently, the regional field was decreased by 140 gammas.

Gimbal-suspended LaCoste and Romberg (L&R) sea gravity meter S-9 measured gravity during the 1969 cruise. L&R stable table shipboard gravity meter S-42 replaced the gimbal-mounted meter for the 1971 and 1973 cruises. Both meters compensate for horizontal and vertical accelerations. The L&R stable table meter also corrects for cross-coupling between horizontal and vertical accelerations. Data obtained in the Panama Basin by the OSS OCEANOGRAPHER for the National Oceanographic and Atmospheric Administration (NOAA) in 1969 and the R/V KANA KEOKI for the Hawaii Institute of Geophysics (HIG) in 1972 provide supplementary data. Figure 4 shows the tracklines for these cruises.

At sea, strip charts record the gravity data and these records are subsequently digitized. The digitization interval of the 1969 data was 15-20 minutes which resulted in an approximate 0.2 pts/km sampling frequency. The sampling frequency for the 1971 and 1973 data is about 0.8 pts/km.

The land base stations, to which the marine gravity meter readings were referenced, for the 1973 cruise were Balboa, Panama (Wh 1056: Woollard and Rose, 1963) and San Diego, California (WA 453: Woollard and Rose; 1963 tied to Worzel, San Diego "f", Worzel, 1965). San Diego was the land base tie for the 1971 cruise (Gemperle,

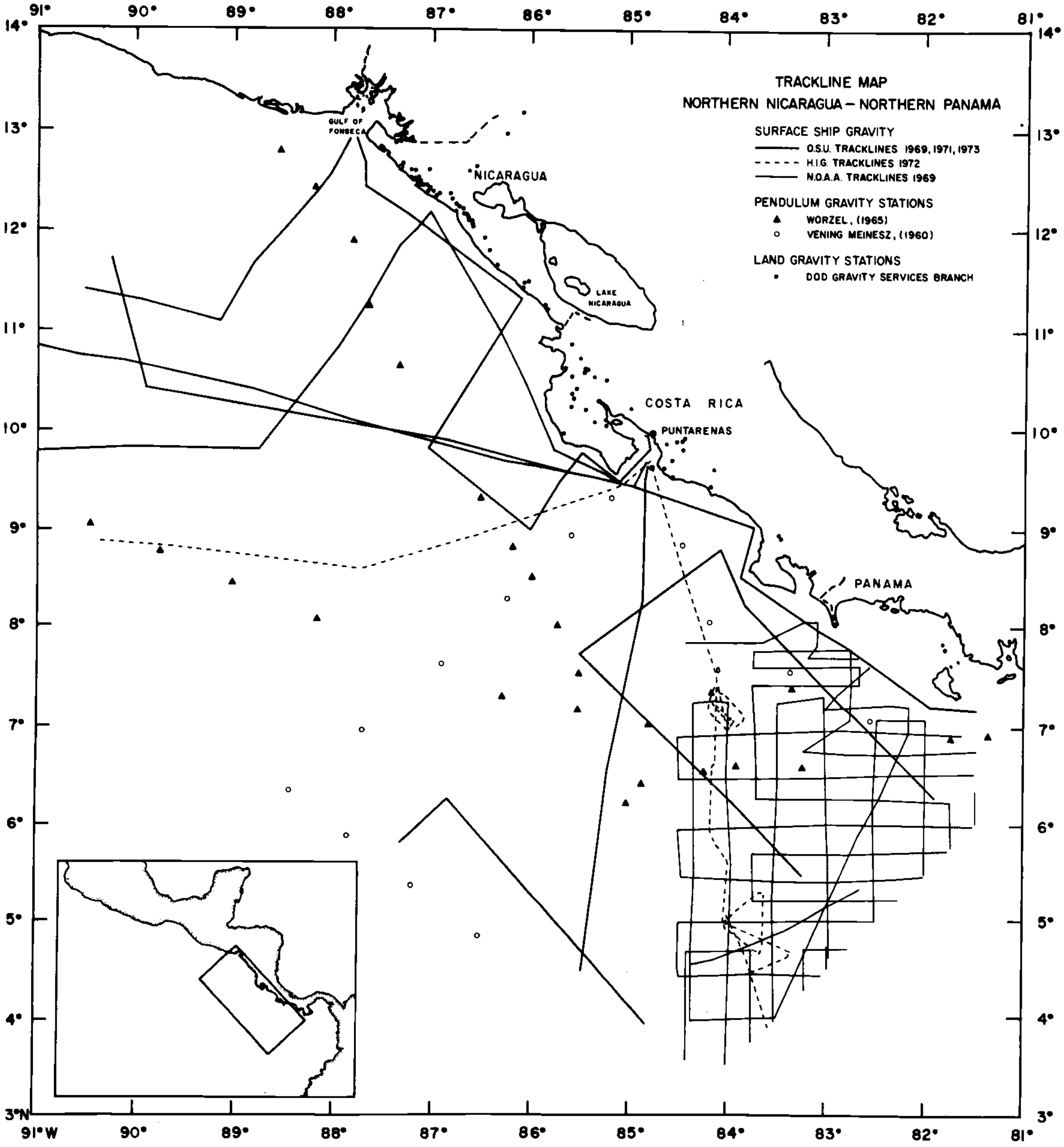

Figure 4. Trackline map showing location of sea and land gravity measurements. Inset shows thesis area in relation to the Central and South Americas.

personal communication). The base ties were used also to determine a meter drift correction for the 1973 data. The meter drift was about 1 mgal for approximately 24 days (Gemperle, personal communication).

Another correction applied to the gravity data was the Eötvös correction which compensated for the change in centrifugal acceleration due to the ship moving on a spherical earth. Precise navigation is needed because this correction depends on the latitude, speed, and heading of the ship. Satellite fixes, ship's speed logs, and gyro headings provide data which yield these three necessary navigational parameters.

Free-air gravity anomalies were calculated by subtracting theoretical gravity from observed gravity. Theoretical gravity was calculated from the International Gravitational Formula (International Association of Geodesy, 1967).

The differences between gravity measurements occurring at the intersections of tracklines indicate a crossing-point error. These differences for 18 trackline crossings indicate a Root-Mean-Square (RMS) uncertainty in gravity measurements of 5.5 mgal for the area west of Nicaragua, Costa Rica, and northern Panama.

INTERPRETATION OF DATA

Free-Air Gravity Anomaly Map

Upon viewing the free-air gravity anomaly map (Figure 5) of the area from northern Nicaragua to northern Panama, two regions are immediately obvious: a northern region having a NW - SE linearity due to the dominance of the large negative gravity anomaly associated with the Middle America Trench, and a southern region exhibiting a complex pattern due to the numerous localized anomalies associated with the Cocos Ridge and the western margin of the Panama Basin.

Off the coast of Nicaragua, an elongate anomaly bounded by a +50 mgal contour coincides with the crest of the seaward wall of the Middle America Trench. At about 11°N. latitude, this gravity anomaly has gravity values greater than +60 mgal. The bathymetric map (Figure 1) shows a topographic high near the location of the +60 mgal anomaly. Assuming a density contrast of 0.97 gm/cm^3 between the water and near surface sediment layers, calculations indicate that the topographic high is only partially responsible for the observed gravity anomaly.

Immediately landward of the above described anomaly, the free-air gravity values decrease rapidly to a -120 mgal forming an elongate gravity low. This prominent negative anomaly associated with

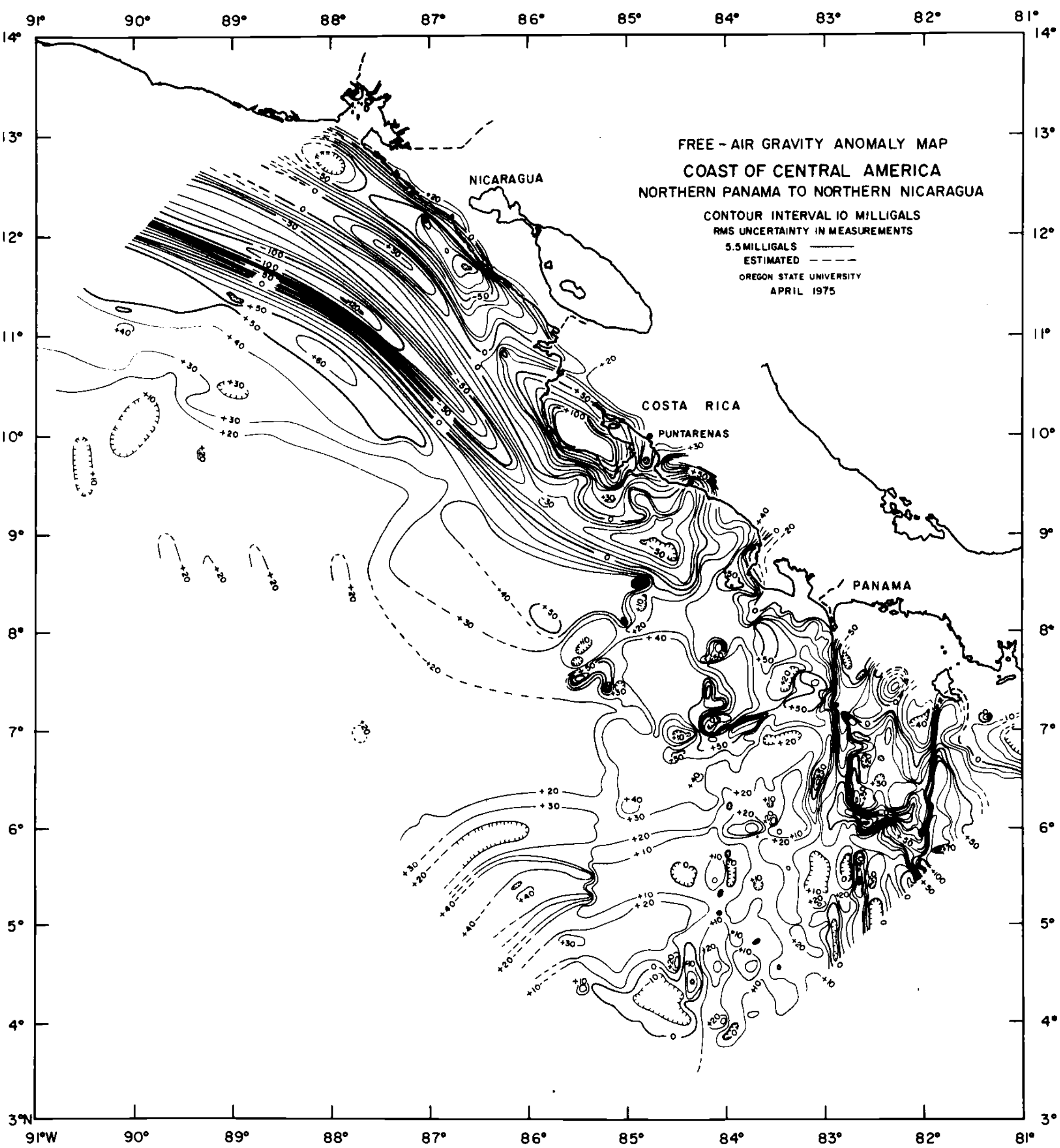

Figure 5. Free-air gravity anomaly map of the continental margin from northern Nicaragua to northern Panama.

the Middle America Trench trends NW-SE, but begins to curve gently southward near 11°N. latitude. The axis of the anomaly is displaced about 3 km landward of the bathymetric axis of the trench. The gravity gradient occurring over the continental slope is less than the gradient observed over the seaward flank of the trench.

Gravity values greater than +30 mgal are associated with the outer margin of the continental shelf. Paralleling the trench on the landward side of this 30 mgal anomaly is a linear negative anomaly. Gravity values from -40 to -50 mgal separate the anomaly into two areas. The northern region has values less than -70 mgal, while the southern area is more extensive and has values less than -90 mgal. The southern portion of the anomaly is approximately 110 km in length. Because there is no topographic relief on the shelf to account for these negative gravity values, this large negative anomaly suggests an absence of mass beneath the shelf, probably indicative of a large sediment-filled basin. Assuming density contrasts of 0.4 and 0.3 gm/cm^3 between the sediment and the underlying rock, calculations suggest that the sediment thickness in the basin is approximately 5 to 7 km for the region enclosed by the -90 mgal contour. A calculation using the same density contrasts for the northern area (-70 mgal) suggests sediment thicknesses of 4 to 5 km.

The gravity values increase toward the coast of Nicaragua, where the free-air anomaly is 0 mgal. Immediately inland the values continue to increase, with the anomaly contours paralleling the coastline.

Off the coast of northern Costa Rica, the axis of the negative anomaly associated with the trench begins to curve in a more eastwardly direction toward central Costa Rica. Near 9.5°N. latitude, the trench anomaly is only -30 mgal, and appears to be pinched off by the +100 mgal values occurring over the Nicoya Peninsula in northern Costa Rica.

The anomaly over the Nicoya Peninsula is oval in shape and about 222 km long. The highest gravity values occur over the middle of the peninsula. Except for a small elevated area near the center of the peninsula the elevations on the peninsula range from 0 to 500 m above sea level, and thus do not account for the abnormally high free-air gravity values found there. This indicates excess mass beneath the surface, and the gravity gradients suggest a relatively shallow depth.

The anomaly associated with the trench becomes more negative southeast of the Nicoya Peninsula and reaches -50 mgal at 9°N. latitude. Here, the anomaly appears to be cut off to the south by increasingly positive values associated with the western margin of the Cocos Ridge, and cut off to the northeast by a positive gravity anomaly occurring over the Harradura Peninsula, slightly southeast of Puntarenas, Costa Rica. Also, two small lobes of the -50 mgal anomaly point landward. One lobe points toward the anomaly over the Nicoya Peninsula, and the other points toward the Harradura Peninsula. A portion of the latter lobe occurs over the continental shelf (Figure 5).

A gravity high occurs over the Harradura Peninsula with values over +100 mgal. The elevations of the terrain also increase away from the coast, which partially explains the increase in the free-air gravity values. This high positive anomaly over the Harradura Peninsula is just southeast of the anomaly over the Nicoya Peninsula and may be related to that particular anomaly.

The positive gravity values between +30 and +70 mgal southeast of the trench anomaly are associated with the landward end of the Cocos Ridge. Due to the high trackline density (Figure 4), relatively shallow water, and high topographic relief in this area, many small, localized anomalies are observed over the ridge crest. Numerous volcanic peaks and basins characterize the topography of the Cocos Ridge (vanAndel et al., 1973). The small, localized gravity highs and low probably indicate the presence of some of these topographic features. The ridge is bounded on the east and south by a +20 mgal contour.

Two major fault zones are associated with the Western Panama Basin; the Panama Fracture Zone and the fracture zone located at 85°20'W longitude (Barday, 1974). The Panama Fracture Zone near 82.5°W. longitude (Molnar and Sykes, 1969) appears as a prominent linear negative anomaly at approximately 83°W. longitude on the free-air gravity map. The northern end of this feature, at about 7.5°N. latitude has values less than -60 mgal. The gravity values of the gravity anomaly increase to 0 mgal at 6.5°N. latitude, before decreasing again near 6°N. latitude. The trend of this negative anomaly zone changes from N-S to E-W at 6°N. latitude. The E-W segment of the anomaly has values less than -50 mgal and is bordered on the east by high positive values between 60 and 100 mgal that relate to the crest of the Coiba Ridge. The anomalies associated with the fracture zone at 85°20'W. longitude are not as distinguishable on the gravity map as those of the Panama Fracture Zone. The left-lateral offset of the positive values, of 20 to 40 mgal, over the Cocos Ridge at about 85.5°W. longitude appears to correspond to the location of the fracture zone. The lack of detail in the contours at and to the west of 85°W. longitude is due to fewer lateral density variations and a sparsity of data.

The region between the two fracture zones has gravity values between +10 and 0 mgal, with some reaching +20 mgal. One exception to this regional gravity range is a narrow N-S anomaly at approximately 82.5°W. longitude, just south of the E-W segment of the anomaly associated with the Panama Fracture Zone. This anomaly has a maximum value of +50 mgal and is paralleled on each side by two anomalies with values of 0 mgal or less. These three anomalous zones seem to correspond to a bathymetric high and two bathymetric lows in the area (Figure 1).

North of the Coiba Ridge and just seaward of the outer edge of the continental shelf are two negative anomalies. These -40 mgal anomalies are part of the "negative anomaly belt" around the northern border of the Panama Basin described by Barday in 1974.

The area south of 10°N. latitude and west of 87°W. longitude appears to average about +20 mgal. This observation is based on one trackline at about 9°N. latitude (Figure 4).

Seismic Reflection Profiles

The seismic reflection profiles are divided into two groups. The first group consists of four profiles (A-A', B-B', C-C', D-D') that cross the Middle America Trench and intersect the continental shelf at right angles (Figure 2). Profiles A-A', B-B', and C-C' are west of Nicaragua and profile D-D' lies west of the Nicoya Peninsula, Costa Rica. Profiles I-II, III-IV, IV-V, and V-VI form the second group. They are along the continental shelf and parallel the coasts of Nicaragua and Costa Rica (Figure 2).

Figure 6 shows the land geology and tectonics for Nicaragua and Costa Rica and also includes the locations of the main tectonic structures of the continental shelf, which the seismic reflection profiles indicate. A bathymetric map (Figure 1) and the trends of structures suggested by the free-air gravity anomaly map (Figure 5) aided in the determination of the approximate strikes of the structures along the shelf.

Middle America Trench

Figure 7 shows the line drawings for A-A', C-C', D-D', while Figure 8 is the line drawing for profile B-B'. The depth scales are based on 1.46 km/sec and only indicate water depth. A velocity of 2.15 km/sec was used to estimate the sediment thicknesses along these profiles seaward of the trench.

Profile A-A', southwest of the Gulf of Fonseca, begins at the approximate crest of the seaward wall of the Middle America Trench. Approximately 0.4 km of sediment covers the seaward flank of the trench. The sediment contains at least one strong internal reflector, which can be traced almost to the trench axis on the reflection records. The sediment and the underlying basement are highly faulted as shown by vertical displacements and reflection hyperbolas (Figure 7). At least one of the fault blocks dips seaward. The trench axis is v-shaped and contains about 0.4 km of sediment. The acoustic basement is faulted beneath the sediment fill.

The sedimentary strata along the shelf in profile A-A' show little deformation. An anticlinal fold occurs about 6 km from the Gulf of Fonseca, the eastern end of the profile. A change in the slope of the shelf exists about 46 km from the Gulf of Fonseca. The water depth at this change in slope is about 0.23 km. The continental slope extends from this point to the trench axis, a total horizontal distance of about 95 km. Several small channels cut the upper slope. The seismic energy was insufficient to detect an acoustic basement on the slope, but there is a lower reflecting surface distinguishable by the numerous reflection hyperbolas, suggesting that the material is broken and contorted. This lower layer forms two main structural highs which in turn form basins on the slope. Disconformities within the sediment in both basins are apparent. The lower basin is deeper and rounder with the sediment lapping onto the continental slope. This basin is about 7 km in width. The structural high terminating the basin is covered with a thin layer of sediment that gradually thickens to a time-thickness of 0.43 sec where it intersects the trench axis. The sediment at the base of the slope appears deformed, possibly by slumping.

Profile B-B' is off the coast of northern Nicaragua (Figure 8). The horizontal distance scale represents trackline distances that correspond to the horizontal scale on the two crustal and subcrustal cross sections described in the next section. The crest of the seaward wall of the trench is near the 280 km mark on the horizontal distance scale. Seaward of the crest, the water depth is about 2 km. The acoustic basement has very irregular topography with numerous seamounts visible, two of which rise above the draped sediment cover

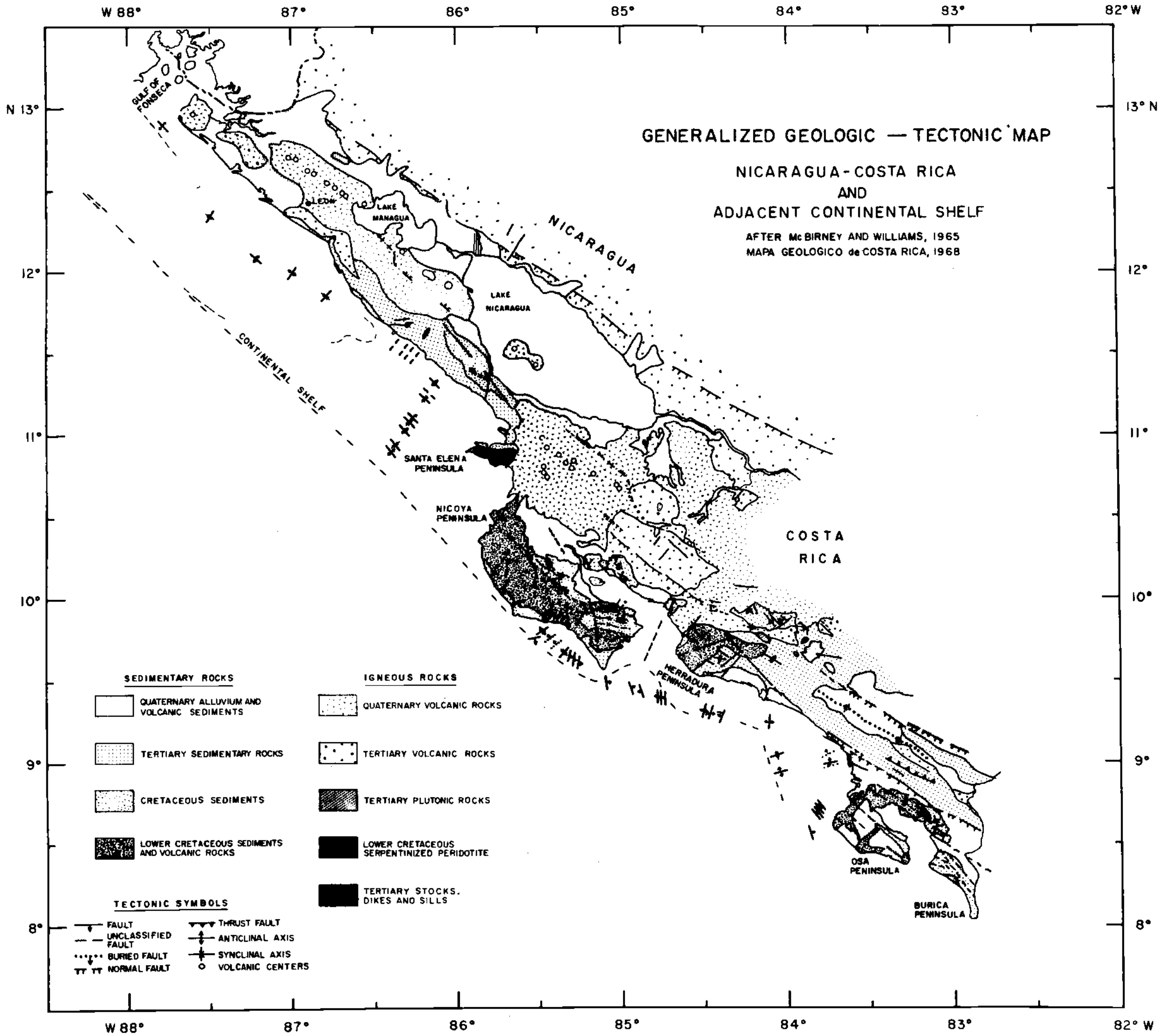

Figure 6. Geologic and tectonic map of Nicaragua, Costa Rica, and adjacent continental shelf. Light dashed lines on continental shelf of Nicaragua outline the Managua Basin.

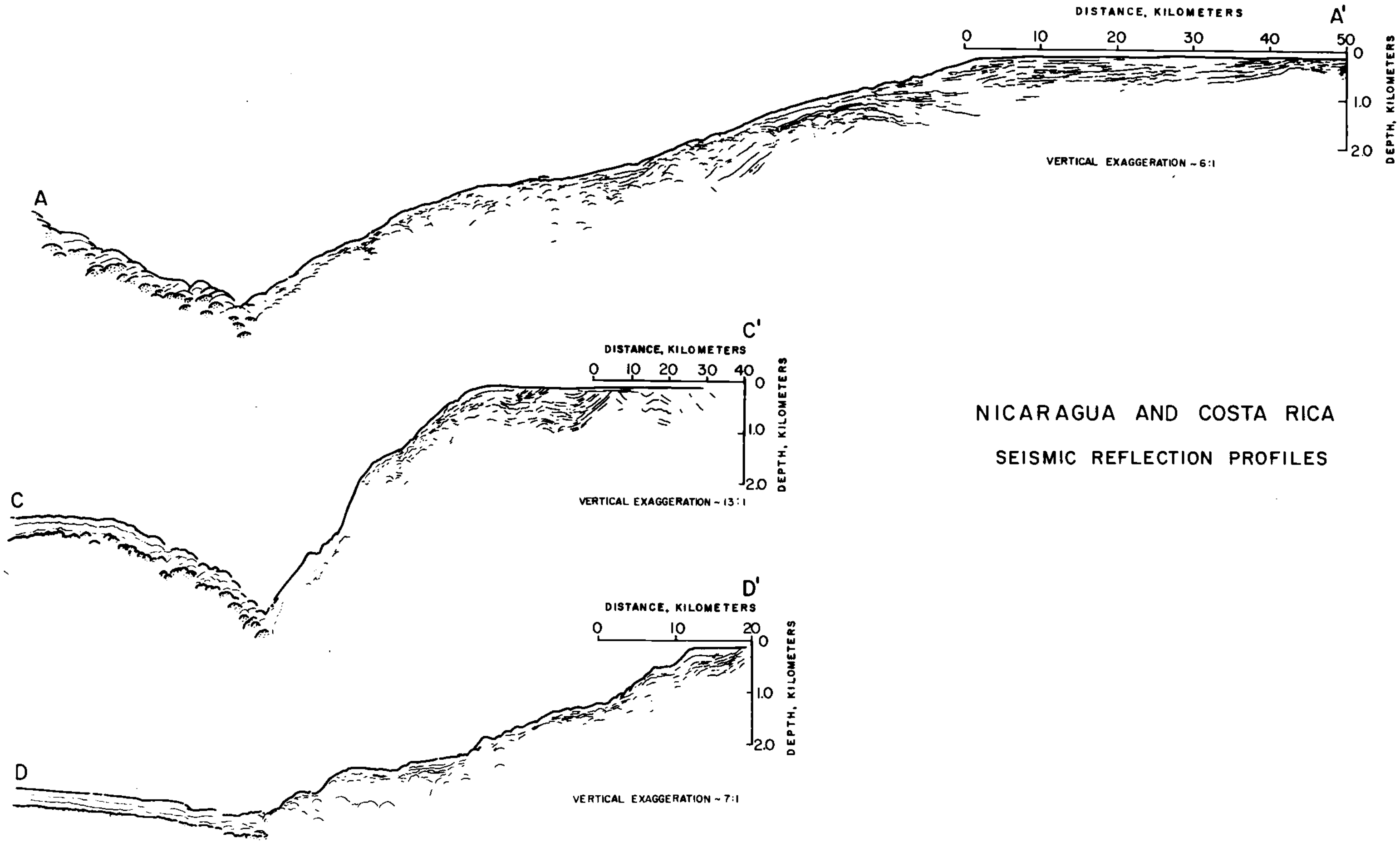

Figure 7. Line drawings of seismic reflection profiles crossing the Middle America Trench and continental slope and shelf. Profiles A-A' and C-C' are off the coast of Nicaragua. Profile D-D' is west of the Nicoya Peninsula in Costa Rica. The vertical scale indicates water depth.

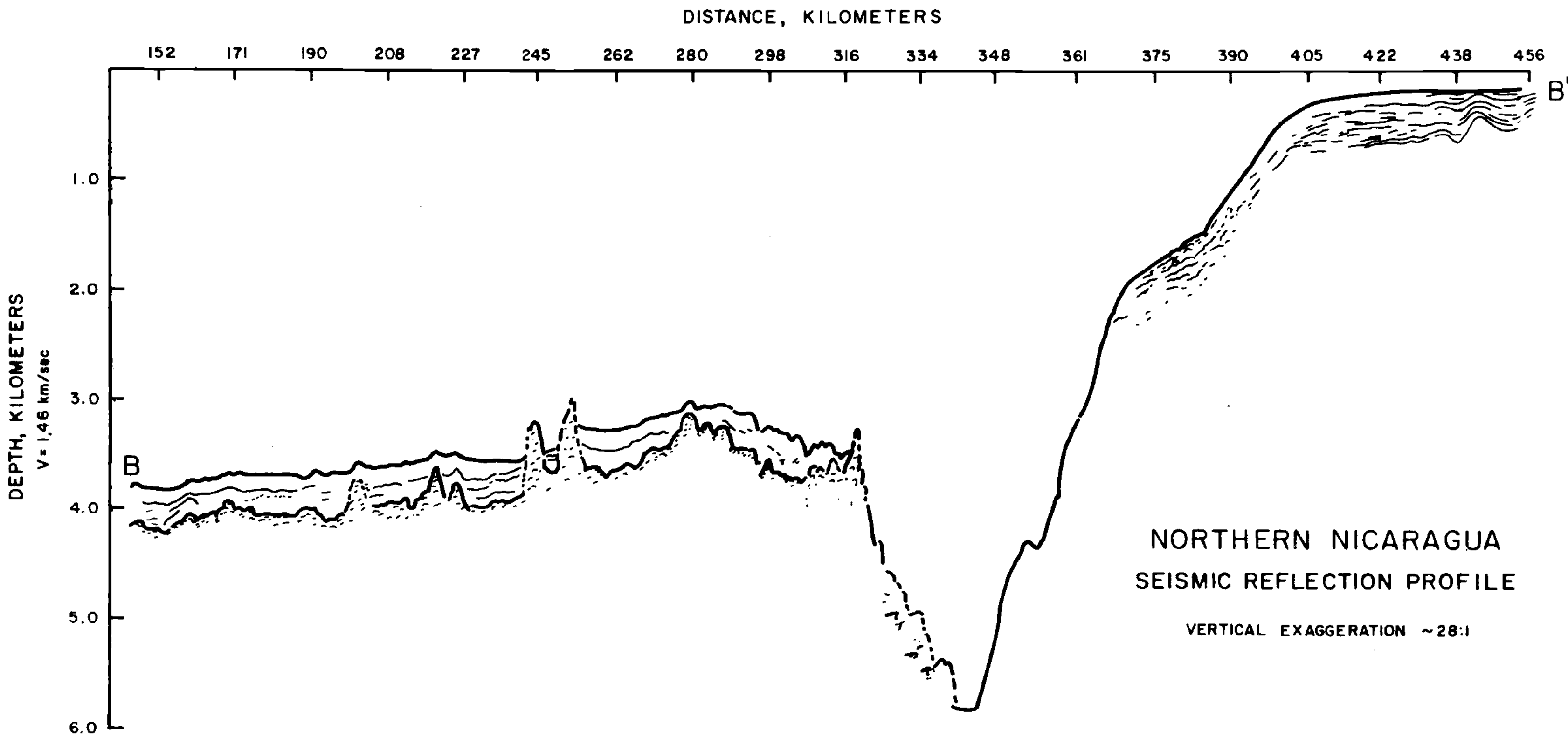

Figure 8. Line drawing of seismic reflection profile B-B'. The profile is west of Nicaragua and coincides with the crustal and subcrustal cross sections. The vertical scale indicates water depth.

near 245 km. The sediment and acoustic basement are highly deformed due to faulting where they deepen toward the trench axis. The sediment in the trench appears to be quite flat, but slightly perturbed adjacent to the continental slope. No acoustic basement is visible in the trench axis.

Folded sediments of undetermined thickness occur beneath the continental shelf. The sediments are folded at approximately 444 km. The continental slope extends from about 405 km to the trench axis at about 340 km. The water depth at 405 km is about 0.12 km. The seismic wave penetration was too shallow to detect an acoustic basement, but in a few places there is a stronger reflector beneath the slope sediments. A bench exists on the upper slope from 369 km to 384 km. The bench is covered with deformed sediments which suggest slumping. A small ledge occurs on the lower slope at about 350 km. No substructure is visible from the bench to the trench axis.

Profile C-C' lies off the coast of southern Nicaragua. The seaward flank of the trench is similar in structure to the two more northern crossings (Figure 7). As along profile B-B', there is a topographic high on the seaward wall, formed by an arching of the acoustic basement. The high is not as pronounced as in the B-B' crossing. Seaward of this bulge where the water depth is approximately 2 km, the sediment drapes over rough topography. Two reflectors are visible within the 0.45 km thick sediment layer. The seaward slope exhibits distinct faulting with vertical offsets of the basement and sediment. Many of the fault blocks dip seaward. Faulting of the acoustic basement and overlying sediment extends to the trench axis where there is about 0.48 km of disturbed sediment.

The sediment on the continental shelf along profile C-C' appears folded forming anticlines and synclines. Figure 6 shows the locations of the axes of these sedimentary structures. A change in the slope of the shelf exists about 63 km from the eastern end of the profile. The continental slope extends from this change in slope to the trench axis, a total horizontal distance of 57 km. The water depth at the crest of the slope is about 0.13 km. The continental slope is almost identical in structure to that in profile B-B'. A bench exists about one half way down the slope and a small ledge occurs about two thirds of the way to the trench axis. As in the previous two crossings, a lower layer is occasionally visible beneath the slope, however, it is not interpreted as acoustic basement.

Profile D-D' is the most southern trench crossing and is just west of the Nicoya Peninsula, Costa Rica (Figure 7). Here the trench is very shallow in comparison to depths at the other crossings. Seaward of the trench axis the sediment thickness remains a fairly constant 0.45 km. Both the acoustic basement and overlying sediment show block faulting near the trench axis. The trench contains about 0.7 km of disturbed sediment and the acoustic basement which dips landward is plainly visible beneath the sediment.

The seismic reflection records (profile D-D') show the sediment beneath the continental shelf to be dipping seaward (Figure 7). The continental slope begins where the water depth is about 0.1 km, about 8 km from the eastern end of the profile. Two layers are visible beneath the slope. The lower layer does not appear continuous and is very broken up, forming several ledges and sediment traps. The upper sediment layer is also contorted, but becomes smooth over a ledge about 26 km from the trench axis. In the sediment pockets, reflectors are visible within the sediment.

Continental Shelf

Figure 2 shows the location of 4 seismic reflection profiles acquired along the continental shelf of Nicaragua and Costa Rica. Roman numerals in Figure 2 reference these profiles. The horizontal distances on the line drawings of the reflection records (Figure 9) refer to trackline distances along the profile. Profile I-II lies along the continental shelf of Nicaragua and has a horizontal distance scale independent of the scale for profiles III-VI located along the continental shelf of Costa Rica. The velocity of sound in water (1.46 km/sec) determined the depth scales. The descriptions of the profiles are from north to south.

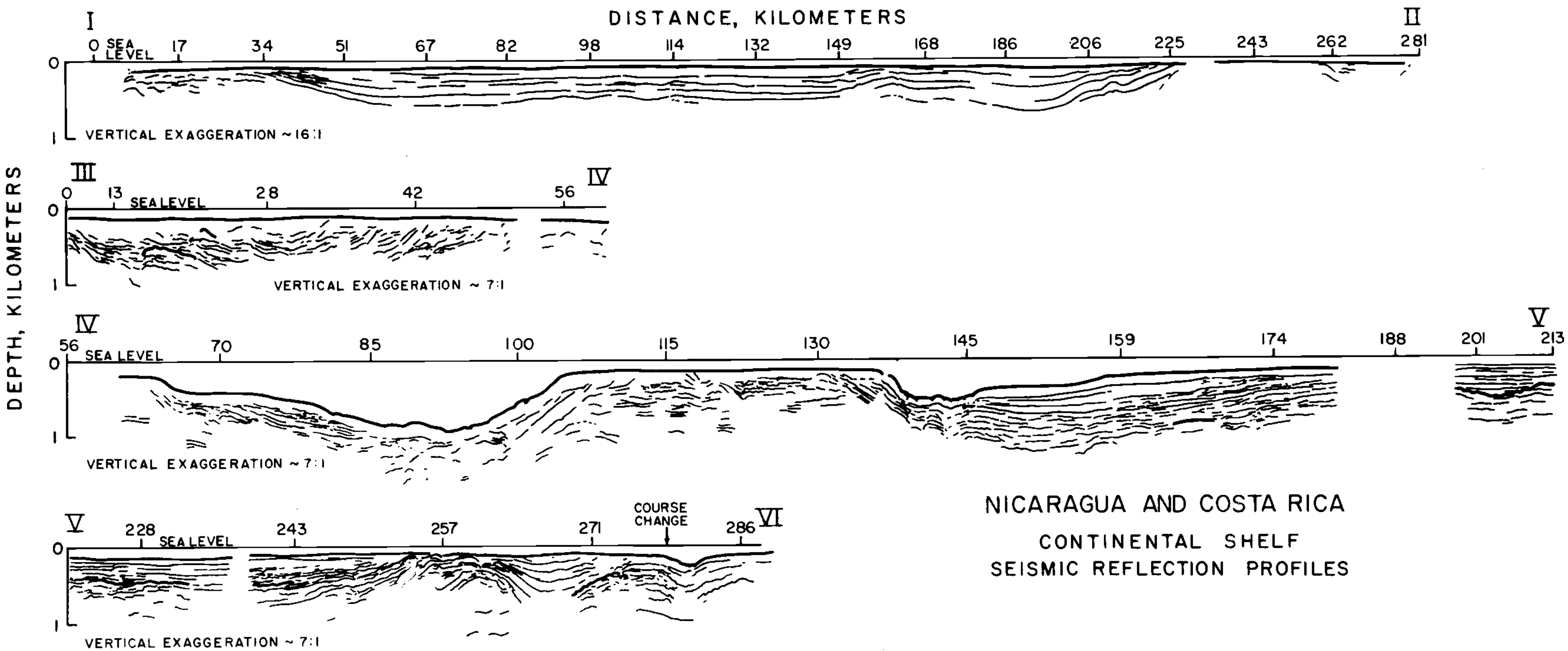

Figure 9. Line drawings of seismic reflection profiles along the continental shelf. Profile I-II lies west of Nicaragua and profiles III-VI lie west of Costa Rica. The vertical scale indicates water depth.

Profile I-II is 281 km long, begins near the Gulf of Fonseca, and ends off the coast of southern Nicaragua about 50 km northwest of the border between Nicaragua and Costa Rica (Figure 2). The seismic reflection records for this profile indicate a sedimentary basin which extends from about 34 km to 234 km. Henceforth, this basin will be referred to as the Managua Basin. The sedimentary layers pinch out to the north on the flank of an anticlinal structure. A portion of this anticline is seen on the eastern end of the seismic reflection profile, A-A' (Figure 7). A dashed line represents the outer boundary of this structure and indicates a strike of N 35°W (Figure 6). An anticlinal fold in the sediments west of central Nicaragua at about 160 km divides the Managua Basin into two sections. The sediments north of this fold are mainly flat-lying. The sediments in the basin to the south appear to be thicker and more deformed. The seismic energy was not sufficient to detect acoustic basement. Another anticlinal structure (about 230 km from the Gulf of Fonseca) terminates the Managua Basin. This feature is almost acoustically transparent, but does appear to be highly faulted and/or tightly folded as suggested by reflection hyperbolas on the record. Light dashed lines in Figure 6 outline the possible boundaries of the Managua Basin. The southeastern boundary on the reflection records coincides approximately with the -80 mgal contour on the free-air gravity anomaly map.

Profile III-VI consists of three smaller profiles that parallel the coast of Costa Rica. The horizontal distance scale is continuous from III-VI.

Profile III-IV is along the southern half of the Nicoya Peninsula. The multiple phases of the outgoing signal obscure the near surface features along the profile. In many places just a reflector or two indicate that some type of structure is present. About 5 km from the beginning of the profile, the records indicate a structural high, which may be either a fold or an uplifted block. Predepositional faulting occurs at 16 km and 22 km and is indicated in Figure 9. The north sides of the two faults are downthrown. The reflectors from about 24 km to the end of the profile at 56 km are broken and contorted. Reflectors dipping in a northerly direction on profile III-IV occur at 33 km, 38 km, and 42 km.

The Nicoya and Osa Peninsulas border profile IV-V to the north and south respectively. A fault locates a change in slope of the continental shelf at 64 km. This fault forms the western boundary of a 40 km wide basin occurring approximately 65 km south of Puntarenas, Costa Rica. The western side of the basin appears to have a larger accumulation of sediment than the eastern side. Between 70 and 85 km a wedge of sediment consisting of continuous reflectors lies between folded and faulted sediments. The reflectors in the axis of the basin are not as strong or as continuous as those appearing on the slope, which suggests a lesser degree of sediment compaction in the basin. Figure 6 shows only the location of the boundary faults of this basin.

The shelf south of the Herradura Peninsula, Costa Rica, between 104 and 137 km is similar to the shelf adjacent to the Nicoya Peninsula in profile III-IV. The reflectors are folded and faulted and suggest near-surface structural highs. A structural high occurs near 130 km and is indicated in Figure 6.

Just southeastward of the structural high, a fault locates another change in slope of the shelf. A basin, shallower than the one to the west on this profile (IV-V), occurs between 137 and 174 km (Figure 9). The "axis" of the basin lies between 139 and 145 km and is a result of block faulting. The central fault block forms a horst and is bordered by sediments that contain only a few distinct reflectors (Figure 9). Two layers are visible beneath the gentle eastern slope of the basin. The slightly deformed lower layer almost pinches out the upper layer near the faulted area of the basin. The upper layer also is slightly deformed near 166 km. A layer consisting of horizontal reflectors overlies a deformed layer from approximately 197 km to the end of the profile at 213 km. The maximum time-thickness of the upper layer is 0.6 sec.

Profile V-VI parallels the western coast of the Osa Peninsula. The seismic reflection records along the shelf recorded the same two layers mentioned above. A post-depositional fault occurs near the beginning of the profile at 226 km, and a predespositional fault occurs at 227 km. The maximum thickness of the upper layer is 0.45 sec at 235 km. A large fold in the second layer forms a structural high with its axis near 257 km, 44 km from the northern end of the profile. The anticline is faulted near its axis. The seismic reflection records suggest the presence of another fold, with a fault near the location of its axis, at 275 km. A small faulted basin exists 281 km from the end of the profile.

The reflection records acquired by Scripps Institute of Oceanography in 1972 crisscross the trench off the coast of Costa Rica (SIO 3 in Figure 2). The locations of the changes in shelf slope along these profiles and the ones just described indicate the outer boundary of the continental shelf (Figure 6). Also, two structural highs and one basin are visible on Scripps' reflection records. Figure 6 shows the location of these structures.

Crustal and Subcrustal Cross Sections

The structures of the continental margin of northern Nicaragua appear quite linear as shown by bathymetry (Figure 1) and indicated by the free-air gravity anomalies (Figure 5). This linearity allows the use of the method by Talwani *et al*. (1959) for computing the gravity over two-dimensional structures. Gemperle (1975) incorporated the previous method in the computer program used to calculate the gravity over the following cross sections.

Two crustal and subcrustal cross sections were constructed along free-air gravity anomaly profile (B-B') located perpendicular to the coast of northern Nicaragua (Figure 2). A compilation of gravity data by the Department of Defense Gravity Services Branch provided information needed to extend the profile onshore. A gravity anomaly map of Central America (Skarmeta, 1974) shows a 0 mgal Bouguer anomaly approximately 100 km from the landward end of the profiles. This gravity value was used as a constraint on the computed gravity curve beyond the controlled area. Gravity data collected by OSU in 1971 (325 km along B-B') and one gravity value from a profile collected by HIG in 1972 constitute the offshore gravity data. The HIG gravity value occurs at the intersection of the HIG profile and an extension of the OSU profile, approximately 150 km seaward of the first OSU gravity value.

The bathymetric records along the profile determine the marine topography. A bathymetric chart (U. S. Naval Oceanographic Office, 1971) provides the water depth for the HIG data point. An assumed velocity of 2.15 km/sec converts seismic reflection time sections to depth sections along profile B-B' (Figure 8). An Operational Navigation Chart of Central America (Aeronautical Chart and Information Center, 1966) provides topographic information for the landward extension of the profile, except where the exact elevation of the gravity station is known.

One seismic refraction station (Shor and Fisher, 1961) located in the trench axis constrains the model. This station is about 56 km northwest of the model (Figure 2), but was projected along the trench axis. The layer thicknesses and velocities indicated by the refraction study are as follows: water--5.13 km, 1.53 km/sec; sediment--1.13 km, 2.15 km/sec; crust--9.71 km, 6.65 km/sec; mantle--8.60 km/sec (Shor and Fisher, 1961). Shor and Fisher assumed a velocity of 2.15 km/sec for the sediment. Because they received no first arrivals for the sediment layer and indistinct second arrivals, they used the velocity reported by Raitt (1956). His sediment velocity was based on reflection data obtained in the central Pacific (Shor and Fisher, 1961). Also, no basement layer was detected at this refraction station; hence the sediment thickness of 1.13 km is a maximum. Even though the basement layer was not detected, its presence was assumed for the models in this study. The velocities listed above were converted to densities with the use of the velocity-density curves of Ludwig et al. (1970). The scatter in the data comprising the curves allowed variation in the selected densities.

In the absence of refraction data, a standard section on the seaward end of the model adds further constraint to the models. The standard section establishes a mass column for the two cross sections along B-B'. The free-air gravity anomaly is assumed to be zero over the standard section. The standard section computed by Barday (1974) for the Panama Basin provided the necessary mass column for the two models constructed for northern Nicaragua. The following layer thickness and densities compose the standard section: water--4.05 km, 1.03 gm/cm^3; sediment--0.46 km, 2.0 gm/cm^3; transition--1.10 km, 2.6 gm/cm^3; oceanic--4.0 km, 2.9 gm/cm^3; mantle--3.32 gm/cm^3. For the two crustal and subcrustal models in this study, the density of the transition layer was changed to 2.7 gm/cm^3. This change was necessary to produce the observed gravity over the trench and use the thicknesses of layers as indicated by seismic refraction. However, the total mass of the column is unchanged.

The mass column on the landward end of the model has to match that on the seaward end to preserve a mass balance. The crustal densities for the continent are the same for both models. The upper crustal density of 2.60 gm/cm^3 seems to be a reasonable average density for the volcanic and sedimentary rocks comprising Nicaraguan geology. Densities of 2.75 gm/cm^3 and 3.0 gm/cm^3 were used for the remaining crustal layers. There are no continental refraction studies near this area of study, but a refraction study in central Mexico (Steinhart and Meyer, 1961) suggests densities that are in close agreement with the crustal densities used.

The gravity controlled portions of these models are placed in the middle of a rectangular block 20, 000, 000 km in length to reduce edge effects. The vertical extent of the model is 50 km. It is assumed that below this depth there are no lateral changes in density (Barday, 1974; Couch, 1969).

Northern Nicaragua Cross Section

Figure 10 shows the first crustal and subcrustal model of the continental margin of northern Nicaragua. The model has its seaward end at approximately 8.8°N, 89.6°W and strikes N38°E (Figure 2). It extends inland about 300 km. This particular profile was selected because it crosses several significant free-air gravity anomalies.

The gravity data collected by the R/V KANA KEOKI (HIG, 1972) furnishes the first gravity point for the profile. It has a value of approximately +22 mgal. Because there is no gravity data available between this point and the first OSU gravity point, the gravity curve is dashed to indicate inferred values. The free-air anomalies increase to a maximum of about +66 mgal over a topographic high seaward of the trench. The gravity values then decrease to about -123 mgal, coinciding approximately with the bathymetric trench axis. Eastward of this prominent low the free-air gravity anomalies increase to approximately -45 mgal and level off before increasing to

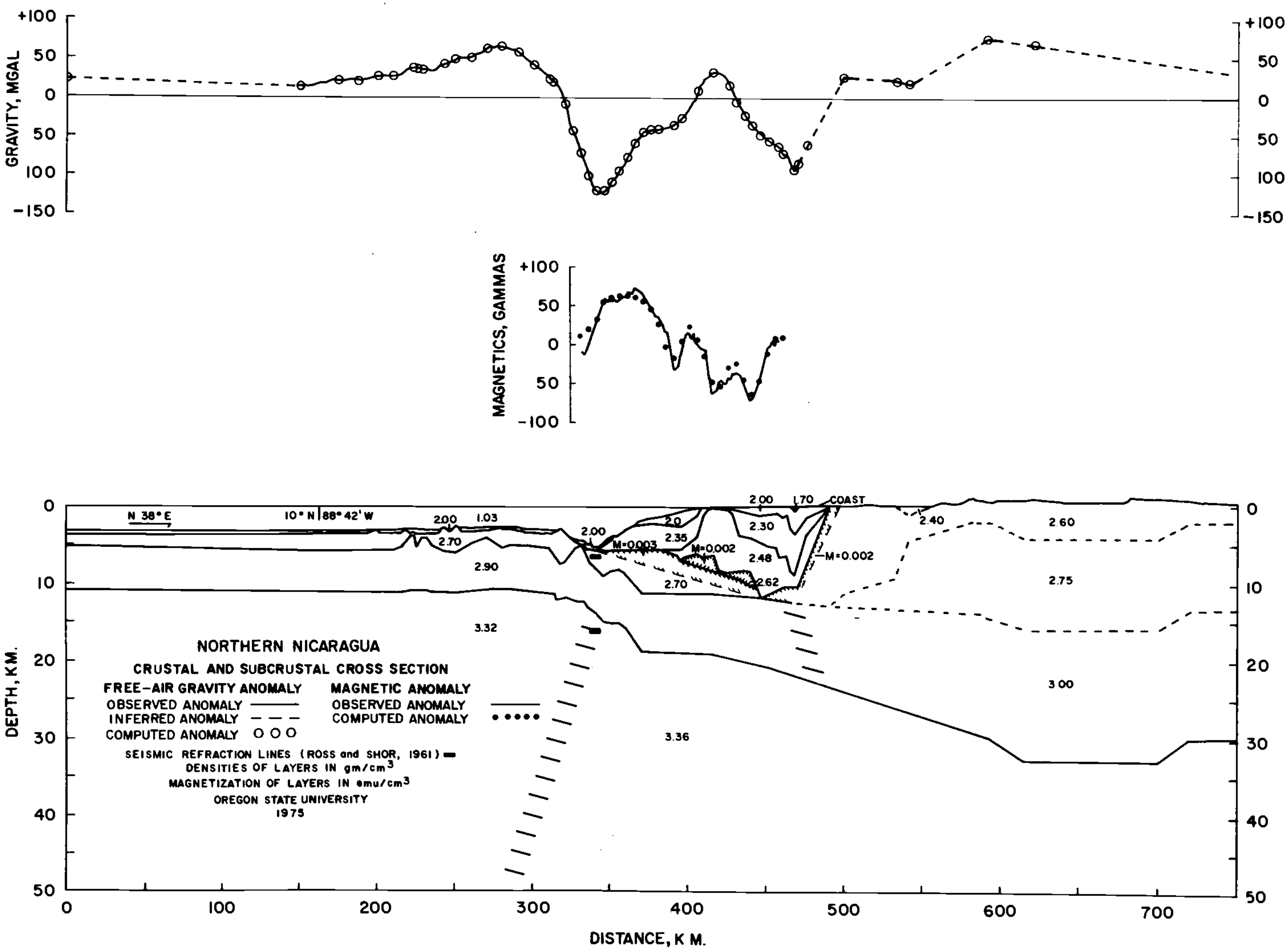

Figure 10. Crustal and subcrustal cross section of northern Nicaragua. Induced magnetization is assumed. The vertical exaggeration is 5:1.

a gravity high of +35 mgal. A gravity low of about -90 mgal is adjacent to the gravity high. Interestingly enough, the +35 mgal peak is a localized anomaly superposed on a regional low. The gravity profile is dashed between the land gravity points, indicating inferred gravity values.

The magnetic anomalies occurring over the continental slope and shelf are graphed beneath the gravity profile. For this model, it was assumed that structures with induced magnetization of the rock beneath the slope and shelf are responsible for the four magnetic peaks observed. This assumption made it possible to model the structures by using the method of Talwani and Heirtzler (1964).

The water depth gradually decreases from about 3.4 km at a horizontal distance of 150 km to approximately 2.8 km beneath the +66 mgal gravity high, and then increases to about 5.5 km in the trench. Maps of land topography indicate cuestas and volcanic ranges that do not exceed 1.22 km in elevation.

It was apparent early in the construction of the model that a laterally homogeneous mantle made it impossible to adhere to the depths indicated by seismic refraction. Hence, the mantle density landward of the trench was changed from 3.32 gm/cm^3 to 3.36 gm/cm^3. Even with this change the thickness of the crustal layer as calculated from the refraction data and the thickness of the trench sediments had to be altered. The arrival time equations for a split spread given by Shor and Fisher (1961) indicate an error range for the input velocities and intercept times. The inclusion of these errors in the calculations for layer thicknesses resulted in a range of thicknesses for each layer. The combined thickness of the transition and oceanic layers used in this model is in this allowable range. Because the sediment thickness of 1.13 km in the trench resulted from an assumed velocity (explained previously) the thickness was decreased. Averaging the sediment thicknesses indicated by the seismic reflection profiles to the north and south (A-A', C-C' in Figure 7) gives a reasonable thickness for this model. Because of insufficient seismic energy, the seismic reflection records coinciding with this cross section indicated no base to the trench sediments. The changes described above resulted in the proper computed gravity values for the trench area.

The boundary between the transition and oceanic layers is very irregular. The roots beneath the seamounts at 250 km and 317 km are overly large. They result from using a two-dimensional method to calculate the gravity over a three-dimensional feature. The upward projections of this boundary and the Mohorovic Discontinuity (Moho) at about 330 km and 360 km suggest a rupturing of the oceanic layer beneath the trench. Also, these boundaries form a slight arch near the trench, and along with the topography are responsible for the gravity high observed at this location.

The Continental slope and shelf substructure is complex. The structures responsible for the magnetic anomalies are hachered. The magnetic anomalies observed over the shelf require the layer of density 2.62 gm/cm^3 to be contorted or broken. The seaward edge of the upper continental crust is the source for the fourth magnetic peak. More of the 2.60 gm/cm^3 layer may exhibit an induced magnetization, but that portion indicated is sufficient to fit the available data. The large block of density 2.48 gm/cm^3, apparently magnetically transparent, accounts for the gravity high observed at the shelf edge. The block appears to be contorted and broken. Immediately landward of this block is a basin 9 km deep. The depth may be slightly overestimated due to a three dimensional effect. The density of the layers in the basin suggest sediments that are compacted with depth. The various sediment layers reflect the irregular boundary of the 2.48 gm/cm^3 block. Because the land geology indicates quaternary sediments along the coast where the profile intersects the shoreline, the basin was continued inland just far enough to incorporate these sediments. The continental slope and shelf may contain more layers, but this was the simplest model that fit both the gravity and magnetic profiles. Also, the number of layers used and their densities, except the block of density 2.48 gm/cm^3, agree with those used in a cross section of Western Guatemala (Woodcock, 1975).

In the landward portion of the model, the small sediment pocket between 532 km and 557 km corresponds to the approximate location of the Nicaraguan Depression. The graben-like continental root beneath the Interior Highlands reaches a depth of about 33 km.

Northern Nicaragua Cross Section (Alternate Interpretation)

The second crustal and subcrustal model for northern Nicaragua is shown in Figure 11. This model is based on the same geophysical data used in the first model, but there are some major structural differences between the two models. In the second model the magnetics are assumed to be remanent and are not modeled. This allows a thin layer of density 2.62 gm/cm^3 to replace the broken layer of the same density in the first model. An attempt was made to correlate the observed magnetic anomalies seaward of the trench with theoretical magnetic anomalies. There was no obvious correlation, possibly because of superposed anomalies generated by numerous seamounts in the area.

The depths determined by seismic refraction are strictly adhered to for this cross section. Because these depths result in a mass deficiency beneath the trench when the densities of the first model are used, the mantle density of 3.36 gm/cm^3 is increased to 3.4 gm/cm^3. The structure beneath the trench basically remains the same, but the upper boundary of the oceanic layer is very close

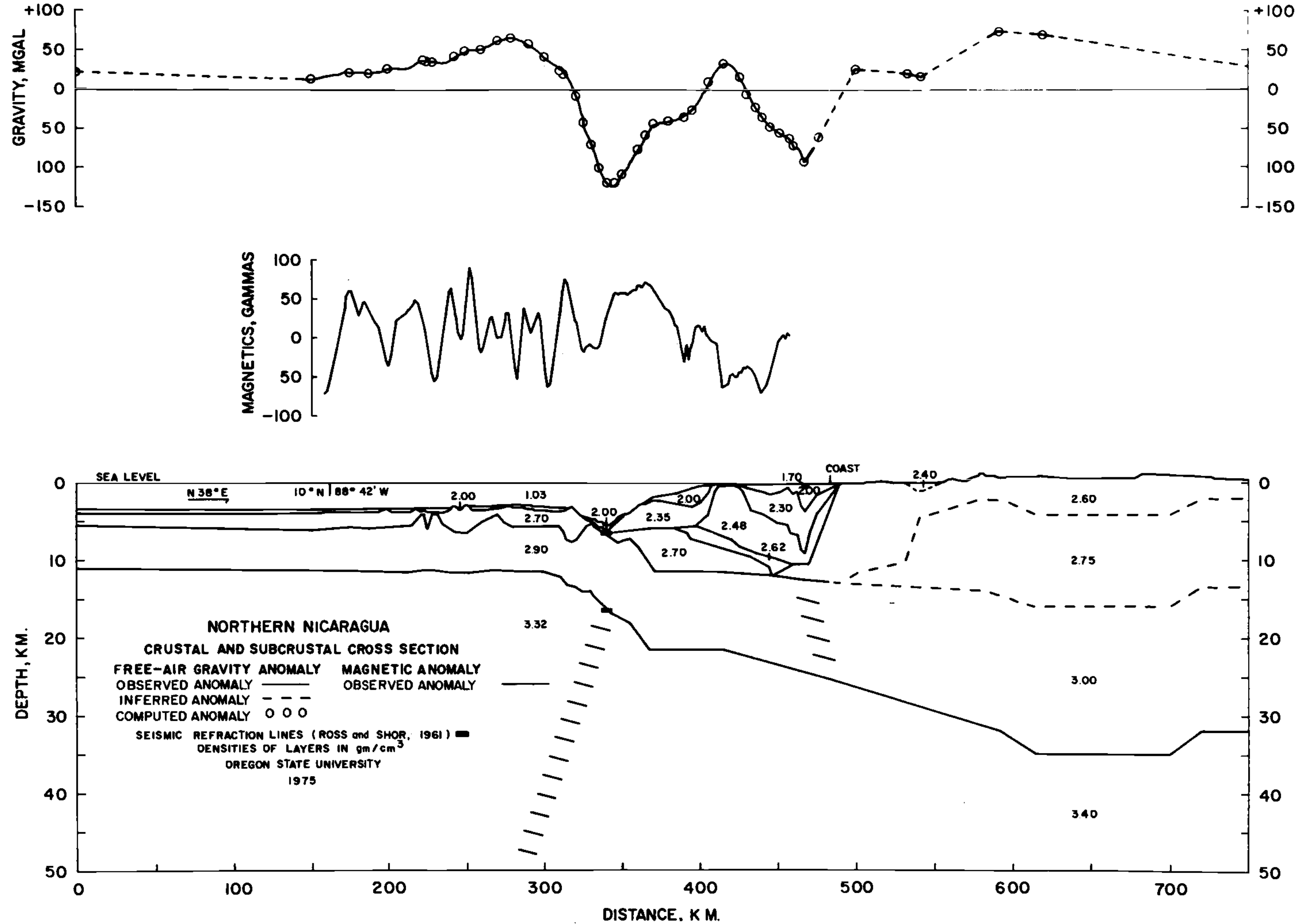

Figure 11. Alternative interpretation of crustal and subcrustal cross section in Figure 10. Remanent magnetization is assumed. The vertical exaggeration is 5:1.

to the base of the sediment fill, resulting in an oceanic layer that is approximately 3.5 km thicker than in the first model. The density change in the mantle requires the Mohorovic Discontinuity landward of the trench to be lowered about 2 km.

DISCUSSION

Trench Area

The seismic reflection profiles show block faulting seaward of the trench axis, and a topographic high at the crest of the seaward wall of the trench (Figures 7, 8). In the crustal and subcrustal cross sections, this topographic high and an arching of the oceanic layer are responsible for a gravity high of over +60 mgal. Watts and Talwani (1974) postulated that the gravity high observed seaward of trenches is accounted for by a flexure of the lithospheric slab during subduction, which in turn forms a topographic high.

Beneath the trench, the two cross sections suggest the presence of a broken and deformed oceanic layer (Figures 10, 11). The rupturing is less grating on the senses in the models drafted at a vertical exaggeration of 1:1 (Figure 12). This deformation is interesting because a cross section of the continental margin of western Guatemala shows no such rupturing (Woodcock, 1975).

Both crustal and subcrustal cross sections also include a high density mantle beneath and landward of the trench (Figures 10, 11). This change in mantle density was necessary to fit the refraction stations in the trench axis, as well as fit the gravity curve. One explanation for this density change is that as the lithospheric slab descends, a phase change occurs in the mantle (Grow and Bowin, 1975).

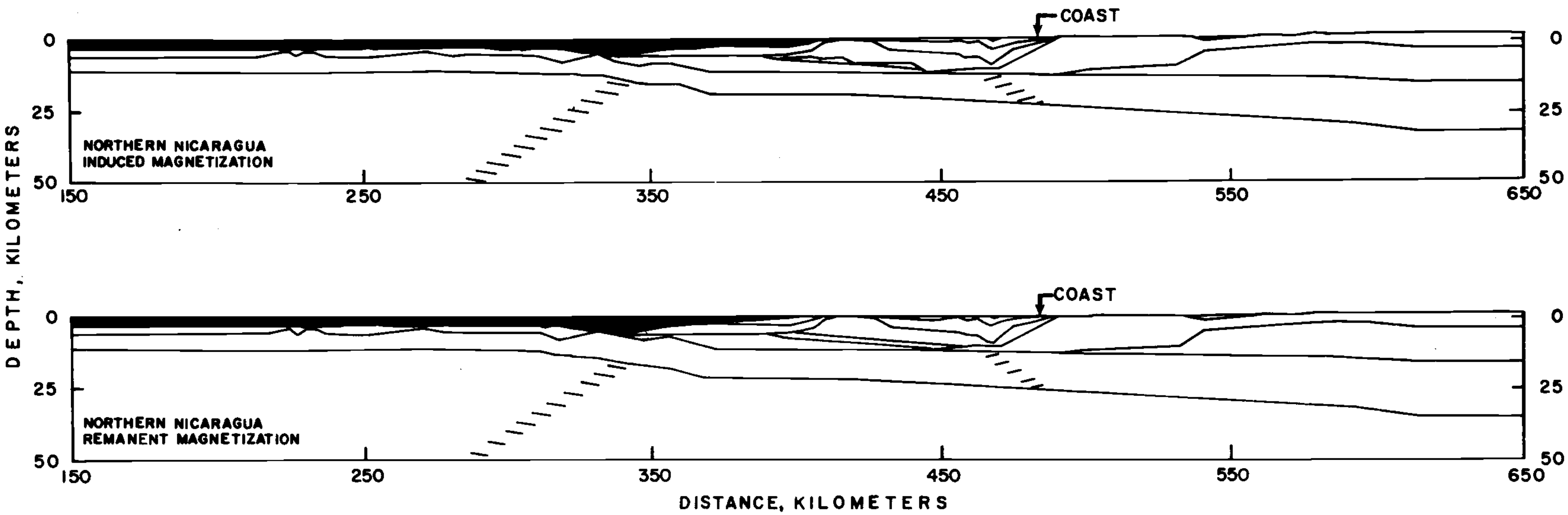

Figure 12. Nicaragua crustal and subcrustal cross sections (Figures 10 and 11) at a vertical exaggeration of 1:1.

Continental Shelf

Managua Basin

A structure suggested by the free-air gravity anomalies (Figure 5) and visible on the seismic reflection records along the continental shelf of Nicaragua (Figure 9) is the Managua Basin. Free-air anomalies as low as -90 mgal occur over this basin at its southern most extremity. The gravity values increase to -40 mgal toward the north along the anomaly and then decrease again to values less than -70 mgal near the Gulf of Fonseca. The basin on the seismic reflection records (Profile I-II) is not as extensive as the free-air gravity anomaly suggests. One reason for this apparent discrepancy is that the negative free-air gravity anomalies indicate an absence of mass beneath the near surface sediments of the shelf, which may or may not be due to a deeper sediment-filled basin. The limited penetration of the seismic waves detected no acoustic basement beneath the basin, but did detect an anticlinal fold that separates the Managua Basin into two smaller basins. This fold is very near the location of the -90 mgal values shown on the free-air gravity anomaly map. The two crustal and subcrustal cross sections of the continental margin of northern Nicaragua show that the -90 mgal gravity values occur over the axis of the 9 km deep Managua Basin. Seaward of the axis of the basin the gravity requires a folded or broken boundary between the two upper sedimentary layers of density 2.0 gm/cm^3 and 2.3 gm/cm^3 that occur in the basin. The anticlinal fold on the seismic reflection records is probably related to this folding within the basin's sediment fill. The steep landward wall of the basin suggests faulting.

The geologic-tectonic map of Nicaragua (McBirney and Williams, 1965) and Costa Rica (Mapa Geologico de Costa Rica, 1968) shows a sequence of Tertiary sediments along the coast of Nicaragua adjacent to the southern portion of the basin (Figure 6). The most recent sediments of the sequence grade into Tertiary ignimbrites and interlayed basaltic lavas (McBirney and Williams, 1965) which occur along the coast of central Nicaragua and slightly northeast of that portion of the free-air gravity anomaly with values from -40 mgal to -50 mgal. Hence, the high negative gravity values may indicate the occurrence of these volcanic rocks within the basin. The Quaternary alluvium and volcanic sediments north of the Tertiary volcanic rocks probably supplied much of the sediment in the northern half of the Managua Basin. The anticlinal structure terminating the basin to the north (Profile I-II, Figure 9) may be an extension of the Quaternary volcanic rocks bordering the Gulf of Fonseca.

Nicoya Complex

A prominent positive anomaly on the free-air gravity anomaly map occurs over the Nicoya Peninsula and has values over +100 mgal. These high positive anomalies are associated with a particular sequence of rocks (the Nicoya Complex) that is exposed on the peninsula. The Nicoya Complex is a large anticlinal feature consisting of marine sediments and pillow basalts (Dengo, 1962). The complex is extensively faulted in north-south and east-west directions (Figure 6). The Nicoya Complex also crops out on the Herradura and Osa Peninsulas in Costa Rica. High positive free-air gravity anomalies occur over the outcrop on the Herradura Peninsula, but the anomalies observed over the same assemblage on the Osa Peninsula are close to zero. However, the free-air gravity anomalies increase to over +40 mgal above the continental shelf adjacent to the peninsula. This suggests that the complex extends offshore and is more extensive than the assemblage on the peninsula.

Geologic studies indicate that rock assemblages like the Nicoya Complex occur in countries to the north and south of Costa Rica. McBirney and Williams (1965) suggest that this group of rocks lies beneath the Pacific Coastal Plain just north of Costa Rica and a large portion of the Interior Highlands. Basement rocks similar in composition to those of the Nicoya Complex occur on the Azuero Peninsula of Panama (Dengo, 1962; Case, personal communication), in eastern Panama, western Colombia and western Ecuador (Case, personal communication). The basement rocks in western Colombia consist mainly of pillow basalts, andesites, and gabbros, and are identified by high positive Bouguer gravity anomalies up to 135 mgal. The rocks are faulted and deformed. They have been interpreted as "a raised segment of oceanic crust that is Mesozoic to middle Eocene in age" (Case, 1969; Case et al., 1970; Case et al., 1971). A gravity high is also associated with the basement rocks in eastern Panama (Case et al., 1971).

The seismic reflection records acquired along the continental shelf of Costa Rica indicate an offshore extension of the Nicoya Complex. Profile III-IV (Figure 9) is along the shelf adjacent to the southern half of the Nicoya Peninsula and shows faulted and contorted strata. At least two of the faults appear to be extensions of onshore faults (Figure 6). However, the downthrown sides are opposite to those onshore as shown on the Tectonic Map of North America compiled by King (1969). This same type of folded, faulted structure occurs south of the Herradura Peninsula and west of the Osa Peninsula (Figure 9). Only one of the faults on the Osa Peninsula is in line with an offshore fault. Faulted basins occur south of Puntarenas and the Herradura Peninsula (Figures 6, 9). The trend of the fault system forming the first basin is nearly north-south and may be related to the almost north-south strike of some of the faults on the Nicoya Peninsula. The faults in the latter basin also trend nearly north-south toward the Herradura Peninsula, but do not appear to line up directly with any of the faults onshore.

The two crustal and subcrustal cross sections of northern Nicaragua enhance the possibility of an offshore extension of the Nicoya Complex. The free-air gravity anomaly map (Figure 5) shows a positive anomaly of over 30 mgal over the outer shelf of Nicaragua and northwest of the large positive anomaly existing over the Nicoya Peninsula. The two crustal and subcrustal sections cross this free-air gravity anomaly (Figures 10, 11). They show the anomaly occurring over a large near-surface block of density 2.48 gm/cm^3. This block overlies a layer of 2.62 gm/cm^3. The near-surface block appears to be folded and deformed in both cross sections; the 2.62 gm/cm^3 layer is extremely contorted in the first model. This latter layer is partially responsible for the magnetic anomalies occurring over the shelf area, which suggests that the layer contains a large amount of mafic or ultramafic rocks. Also, the density of 2.62 gm/cm^3 is very close to the average density of 2.6 gm/cm^3 calculated for the Nicoya Complex by Woodcock (1975). The density and non-magnetic character of the overlying block suggests a sedimentary origin. Both of these layers have characteristics similar to those of the Nicoya Complex, and are interpreted to be similar in origin to or a continuation of the Nicoya Complex.

This interpretation is in accord with the work of Woodcock (1975) off the coast of western Guatemala. He found that a large layer of density 2.62 gm/cm^3 greatly contributed to a shelf gravity and magnetic high, and interpreted it as being similar in origin to the Nicoya Complex. Seely et al. (1974) also hypothesize that the Nicoya Complex occurs beneath the continental shelves of Nicaragua, El Salvador, and Guatemala.

The highest present elevation on the Nicoya Peninsula is 0.5 km and the block of density 2.48 gm/cm^3 is 0.4 km below sea level. This maximum difference in elevation of 0.9 km suggests that there may be faults striking NE-SW between the Nicoya Complex onshore and the postulated offshore complex.

The work of Carr et al. (1974) also suggest the presence of these NE-SW faults. After observing the lineations of volcanoes and distributions of shallow earthquakes near the coasts of Nicaragua and Costa Rica they concluded that transverse structures divide the continental margin in this area into segments. Outcrops of Nicoya Complex rocks on the Nicoya and Herradura Peninsulas occur in the segment consisting of the northern half of the continental margin of Costa Rica. The segment along southern Nicaragua includes a seaward extension of the positive anomaly associated with the Nicoya

Complex on the Nicoya Peninsula. The material interpreted as Nicoya Complex in the cross sections occurs in the segment involving the continental margin of northern Nicaragua.

Origin of Geologic Structures

Seely et al. (1974) presented a thrust model for the formation of continental slopes. Underthrusting of the oceanic plate beneath the continental plate results in thrusts and folds beneath the slope. This thrusting and folding results in a separation of the sediment cover and the transition layer. There is seismic evidence for this separation (Seely et al., 1974). As the plate underthrusts, sediment wedges, possibly folded, accrete to the continental slope. Each new accreted wedge causes the pre-existing thrust blocks to be uplifted and tilted landward. Seely et al. (1974) used the Nicoya Complex as a possible example of this imbricate thrusting.

Prince and Kulm (1975) prefer an imbricate thrust model for the continental margin of Peru from 6° to 10°S. latitude. They found that in this area the oceanic basement is involved in the faulting and uplift. In their description of their model, they also mentioned the possibility of a basin on the landward edge of the shelf.

Imbricate thrusting which involves the crust and upper mantle as well as the sediment cover is postulated as the process which formed the shelf and slope off Nicaragua. The involvement of the crust and upper mantle in the imbricate thrusting explains the presence of mafic and/or ultramafic rocks in the upper shelf. This model for the origin of the geologic structures off Nicaragua may not hold for the southern continental margin of Costa Rica. The subduction of the Cocos Ridge obviously affects the surrounding area as evidenced by the termination of the Middle America Trench northwest of the ridge (Figure 1). The topography near the ridge is more three dimensional in appearance (Figure 1) when compared to the linear structures northwest of the Nicoya Peninsula. Whether or not the Cocos Ridge is the result of the Cocos plate passing over a hotspot (Hey, 1975) or a portion of an ancestral ridge (van Andel et al., 1971), it must have collided with the Middle America Trench sometime during the late Tertiary Period. This collision may have elevated the Nicoya Complex of Costa Rica to its present position.

It is noted that this postulated mechanism of formation of the Nicoya Complex disagrees with the geologic interpretation by Dengo (1962). He infers that the graywackes and conglomerates were formed in shallow water. If this is the case, the origin described in this paper which argues for a formation in the deep sea is erroneous. However, this does not affect the validity of the crustal and subcrustal models and the interpretation of the seismic reflection data; it only affects the final interpretation of the cross sections.

CONCLUSIONS

The Nicoya Complex of Costa Rica is an intriguing rock assemblage of marine sediments and pillow basalts. This complex is associated with positive free-air gravity anomalies as high as 110 mgal. The faults and folds observed on the seismic reflection records acquired along the continental shelf off Nicaragua and Costa Rica suggest an offshore continuation of the Nicoya Complex.

The two crustal and subcrustal models further suggest this offshore continuation. These models show that a large block of density 2.48 gm/cm^3 is mainly responsible for a +35 mgal high that occurs over the outer margin of the continental shelf of Nicaragua. This block overlies a layer of density 2.62 gm/cm^3 that appears highly broken in the first model where this layer is assumed to have induced magnetization. The density of this layer is very close to an average density for the Nicoya Complex calculated by Woodcock (1975). The block of density 2.48 gm/cm^3 and the layer of density 2.62 gm/cm^3 are interpreted as being a continuation of the Nicoya Complex or a similar structure.

An imbricate thrust model provides an explanation for the occurrence of Nicoya Complex type rock near the shelf surface and the present elevation of the Nicoya Complex along the coast of Costa Rica. Considering the data available at this time, this model is the preferred interpretation for the origin of the Nicoya Complex even though it is in contrast with the geologic origin presented by Dengo (1962). The imbricate thrust model not only accounts for the origin of the Nicoya Complex but also the origin of the other structures beneath the shelf and continental slope.

This model proposes the material of density 2.35 gm/cm^3 beneath the slope in the two cross sections to be accreted and slumped sediments. These sediments, compacted by numerous sedimentary wedges, are being accreted to the continental slope by the underthrusting oceanic plate. The underlying layer of density 2.7 gm/cm^3, which is in part responsible for the magnetic anomalies observed over the shelf, probably contains sediments from the oceanic plate and a large amount of basalt derived from a ruptured oceanic crust. During the underthrusting of the oceanic plate, the slope and outer shelf are uplifted and tilted landward, forming a basin beneath the portion of the shelf nearest the land. Off the coast of Nicaragua, this postulated basin is the Managua Basin.

Several of the major fault zones in Nicaragua and Costa Rica have the same NW-SE trend as that of the Managua Basin. It should also be noted that these faults are approximately at right angles to the direction of motion of the Cocos Plate--N37°E as indicated by the poles of rotation given by Minster et al., 1974. Hence, in this area the subduction process, which includes possible imbricate thrusting that occurs as the Cocos plate underthrusts Central America at 10 cm/yr, may be a major cause of the faults in Nicaragua and Costa Rica.

The segmentation of the continental margin of Nicaragua and Costa Rica as described by Carr et al. (1974), the difference in elevation of the onshore and offshore locations of the Nicoya Complex, and a ruptured oceanic layer beneath the trench suggest lateral variations in the subduction process. The northeast-striking faults near the Nicaraguan Depression also may be related to this variation in subduction (Carr et al., 1974). The Cocos Ridge further complicates the subduction process along southern Costa Rica. The subduction of the ridge which began during late Tertiary times probably caused or aided in the uplift of the Nicoya Complex in Costa Rica.

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