A free-air gravity anomaly map of the continental margin of Peru between 12° and 18° S. Lat. shows a -110 to -220 mgl anomaly associated with the Peru-Chile Trench, a -60 mgl anomaly over the Pisco Basin on the continental shelf, and -120 mgl anomaly over the Mollendo (or Arequipa) Basin on the upper continental slope. Anomalies observed over the continental slope and shelf consist of slope and basin anomalies superposed on a very large, broad regional anomaly.

The approximately zero mgl anomaly observed in the region of the Nazca Ridge indicates the ridge is isostatically compensated. A structural model constrained by the observed gravity anomalies and seismic refraction data indicates that compensation is due to a crust approximately 8 km thicker and about 0.04 g/cm³ less dense than the oceanic crust on either side of the Nazca Ridge. Gravity anomalies
are consistent with mass distributions expected at the Peru-Chile Trench as a consequence of subduction of the Nazca Ridge and the Nazca Plate.

Crustal and subcrustal cross sections constrained by free-air gravity anomalies, seismic refraction data, and geologic information indicate approximately 2 km of crustal thinning seaward of the trench on the southeast side of the Nazca Ridge but no crustal thinning on the northwest side of the ridge. Crustal thickness increases from approximately 10 km near the trench to about 25 to 30 km under the southwestern flank of the Andes and to approximately 70 km under the Andes. The crust is inferred to be 33 km thick under the Amazon Basin. A cross section north of the Nazca Ridge suggests a rupture of the crust at depth under the coast mountains, and earthquake hypocenters projected onto this cross section indicate a relatively shallow, nearly horizontal Benioff zone under the Andes and the Amazon Basin. A cross section south of the Nazca Ridge does not show these features, hence a different subduction process on each side of the Nazca Ridge is indicated.

Free-air gravity anomalies indicate a structural high extending northwest from 17° S. Lat. along the coast, the Paracas Peninsula and nearly 100 km offshore along the edge of the continental shelf. Computations based on gravity data suggest the Pisco Basin immediately east of this structural high contains approximately 2.2 km of
sediment. A similar computation for the Mollendo Basin yields a sediment thickness of approximately 1.4 km.

Gravity anomaly patterns are consistent with uplift beneath the continental shelf edge and upper slope and suggest a continental margin composed of compacted, dewatered sediments of both continental and oceanic origin.
Gravity Measurements and Their Structural Implications for the Continental Margin of Southern Peru

by

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# TABLE OF CONTENTS

I. INTRODUCTION 1

   Previous Work 2

   New Data 13

II. FREE-AIR GRAVITY ANOMALY MAP 15
    CONTINENTAL MARGIN OF SOUTHERN PERU

III. CRUSTAL AND SUBCRUSTAL CROSS SECTIONS 27

   Geophysical Constraints 27

   The Mollendo Cross Section 31

   The Nazca Ridge Cross Section 37

   The Pisco Cross Section 40

   The Pisco and Mollendo Basin Cross Sections 48

      The Pisco Basin 50

      The Mollendo Basin 53

IV. DISCUSSION 58

V. CONCLUSIONS 73

   BIBLIOGRAPHY 75
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Trackline map of the area off southern Peru</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Free-air gravity anomaly map of the area off southern Peru</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>Bathymetry map of the area off southern Peru</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Profile index map</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>Mollendo crustal and subcrustal cross section</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>Seismic reflection of the margin along the Mollendo profile</td>
<td>36</td>
</tr>
<tr>
<td>7</td>
<td>Nazca Ridge crustal and subcrustal cross section</td>
<td>38</td>
</tr>
<tr>
<td>8</td>
<td>Pisco crustal and subcrustal cross section</td>
<td>41</td>
</tr>
<tr>
<td>9</td>
<td>Seismic reflection of the margin along the Pisco profile</td>
<td>46</td>
</tr>
<tr>
<td>10</td>
<td>Mollendo and Pisco cross sections shown at 1:1 vertical exaggeration</td>
<td>47</td>
</tr>
<tr>
<td>11</td>
<td>Pisco Basin upper crustal cross section</td>
<td>51</td>
</tr>
<tr>
<td>12</td>
<td>Seismic reflection across the Pisco Basin</td>
<td>52</td>
</tr>
<tr>
<td>13</td>
<td>Mollendo Basin upper crustal cross section</td>
<td>54</td>
</tr>
<tr>
<td>14</td>
<td>Seismic reflection across the Molendo Basin</td>
<td>56</td>
</tr>
<tr>
<td>15</td>
<td>Earthquake hypocenters plotted on Pisco and Mollendo sections</td>
<td>59</td>
</tr>
</tbody>
</table>
The 10 cm/yr convergence rate indicated by Minster et al., (1974) between the Nazca Plate and the South American Plate would be expected to produce significant tectonism along the western continental margin of South America. The dominant morphologic feature along this margin is the steep topographic gradient between the Peru-Chile Trench and the Andes Mountains, often exceeding 12 km elevation change over a horizontal distance of 250 km. The structure of the continental margin of southern Peru is of particular interest because of interaction between the large, aseismic Nazca Ridge and the continental margin near 15° S. Lat.

Gravity measurements made in 1972 and 1974 aboard Oregon State University's R/V Yaquina enable presentation here of a detailed free-air gravity anomaly map of the Peruvian margin between 12° and 18° S. Lat. These measurements constitute a portion of the data gathered for the Nazca Plate Project in the International Decade of Ocean Exploration program, a project conducted jointly by Oregon State University (OSU), Hawaii Institute of Geophysics (HIG), and the Pacific Oceanographic Laboratory (POL-NOAA).

This dissertation discusses the structural implications of the
gravity anomalies. Five cross sections are constructed to illustrate the density structure necessary to produce the observed gravity field. While these structural models are not unique, they provide a useful and reliable constraint on alternative models of postulated geologic structures.

Previous Work

Surveys for submarine cable routes discovered the Peru-Chile Trench about 100 years ago (Fisher and Raitt, 1962) and Murray (1899) published charts of the trench that are very similar to bathymetric charts available in 1950 (Fisher and Raitt, 1962). Schweigger (1947), as indicated on his chart of 'La Fosa de Lima', apparently named the Nazca Ridge (Fisher, 1958) after the Punta Nasca, rather than the inland city of Nazca. This alternate spelling persists to the present (Fisher, 1958; Fisher and Raitt, 1962; Hayes, 1966 and 1974). The Generalized Geology Map of Peru (Anonymous, 1969) is the first publication known to the author using the spelling Nazca for the ridge.

During Scripps Institution's Expedition Downwind during the International Geophysical Year (IGY), 1957-1958, the R/V Horizon and R/V Spencer F. Baird spent 41 ship days in the region of the Peru-Chile Trench and shot five two-ship seismic refraction lines near Antofagasta, Chile, and three more near Callao, Peru, southwest of Lima, Peru (Fisher, 1958). In addition to these eight seismic...
refraction lines in the vicinity of the trench, 3 two-ship refraction lines were shot near the Nazca Ridge, and 28 others elsewhere. The Nazca Ridge refraction results indicated the mantle was "perhaps as much as" 16.6 km below sea level, which is within 0.4 km of the result reported in this paper for refraction line 3'-4 (Section II). Fisher (1958) also observed similarities between the Nazca Ridge and the Tehuantepec Ridge off the coast of southern Mexico.

Fisher and Raitt (1962) and Hayes (1966) used the refraction lines from Expedition Downwind for depth control on cross sections crossing the Peru-Chile Trench near Antofagasta and Callao, and Ocola and Meyer (1973) used the lines near Antofagasta for depth control on two cross sections extending from the oceanic plate through the Andes. Lines DW 22 and DW 23 (Figure 4) are from Expedition Downwind and used for depth control on 2 of the cross sections in this paper (Section III).

Eleven land gravity measurements in Peru were made in 1941 by Aslakson and Swick (1943) as part of observations in both Peru and Columbia, but the very large negative anomaly associated with the Peru-Chile Trench remained for Wuenschel (1952) to discover when he made pendulum measurements in 1947 aboard the submarine USS Conger. Surface ship gravity data obtained by the R/V Vema in 1961, 1962, and 1963 and the R/V Conrad in 1965 greatly improved the resolution of the gravity anomaly field, making the Peru-Chile Trench
one of the best mapped deep ocean trenches (Hayes, 1966). The data showed the gravity lows associated with the trench extending far south beyond the end of the topographic trench near 33° S. Lat., ending near the tip of South America at 57° S. Lat. This made the 'trench' a structural feature about 5500 km long, with the north end identified at 8° S. Lat. Fourteen trench crossings by the R/V Vema and R/V Conrad occur along this 5500 km segment, or about one every 400 km, however, there are none between 12° and 18° S. Lat.

Hayes (1966) suggested extending the gravity low associated with the Bolivar Geosyncline in Columbia south to about 16° 30' S. Lat. with a gap between 2° N. Lat. and 10° S. Lat. He noted that the northeast end of the Nazca Ridge is isostatically compensated, and disagreed with Menard's (1964) suggestion that the Nazca Ridge divides the trench into distinct regions. Hayes' (1966) crustal cross sections near Callao and Antofagasta show pronounced crustal thinning near the seaward side of the trench.

Crustal thinning seaward of trenches in regions where a modest gravity high occurs over the thinned crust has been explained as caused by upward flexure of the oceanic plate as it bends to descend into the trench (Couch et al., 1970; Hanks, 1971; and Watts and Talwani, 1974). As an alternative to requiring crustal thinning to produce the observed gravity high, Grow and Bowin (1975) suggest a descending slab that is 0.05 g/cm³ more dense than surrounding
mantle material down to 300 km below sea level. They explain this model as resulting from temperature disequilibrium in the downgoing slab. However, Watts and Talwani (1975) state that downgoing slabs under island arcs are either compensated in some manner or have a very low density contrast, and details of the configuration of the slab cannot be obtained from gravity data alone. Furthermore, Hayes (1974) points out that the model of Grow and Bowin (1975) shows residual gravity anomalies that would probably require some crustal thinning to eliminate. Hussong et al., (1975b) report that seismic refraction data indicates a crustal thickness about 2 km thicker near 8° S. Lat., 82° W. Lon. than generally observed on the Nazca Plate, and suggests that it "may be caused by compression as the crust enters the subduction zone." However, no outer gravity high is observed along the trench north of 9° S. Lat. where the Mendana fracture zone intersects the Peru Trench, whereas the outer gravity high is observed south of this intersection (Hussong et al., 1975).

The crustal thinning controversy may be moot, however, because Hussong et al. (1973 and 1975) suggest that refraction data from the Nazca Plate implies non-uniform densities in the uppermost 15 to 20 km of the mantle, and he states that measurements in other parts of the world by Hales (1969) and Odegard (1975) show similar results for oceanic mantle. Furthermore, Koch (1970) notes that the gravity field deduced from satellite observations indicates density
variations as deep as 100 km below sea level.

Accumulation of relatively low density sediments on the landward flank of the trench (Hayes and Ewing, 1970) contributes significantly to the gravity minimum observed over trenches, and beside the Peru-Chile Trench secondary gravity lows are caused by slope basins (Hayes, 1974).

Marked variation in topography and gravity anomaly patterns delineate eight tectonic provinces along the eastern edge of the Nazca Plate between the equator and 33° S. Lat. (Getts and Rose, 1975). Boundaries between these provinces can be traced several hundred km out onto the plate, and they correlate with variations in volcanism and seismic activity observed inland. The Nazca Ridge province lies between a Central Peruvian province and an abyssal province.

Land seismic refraction data include unreversed lines shot in 1956 by the Carnegie Institute and a reversed line shot in 1968 by the Carnegie Institute with the assistance of the University of Wisconsin and the University of Texas. The 1956 results were reported by Tatel and Tuve (1958) and Aldrich et al., (1958) but re-interpreted by Woollard (1960), and include a line on the western flank of the Andes (line 890 in Figure 4) and a line farther south on the altiplano. Results from these lines indicate a crustal thickness of 65 to 70 km under the altiplano, and about 50 km for line 890 under the flank of the Andes. The 1968 data, also on the altiplano, were interpreted by Ocola et al.,
(1971) and indicate a crustal thickness of 71 to 73 km. This line also appears in Figure 4 and is designated 'Carnegie'.

Ocola and Meyer (1973) constructed two cross sections from the Pacific Ocean to the Amazon Basin using the land and sea refraction data described above for depth control, and fitting gravity data from Hayes (1966) at sea and Kausel and Lomnitz (1969) on land. Time delays in earthquake seismic wave arrivals at recording stations on the altiplano compared with coastal stations (Sachs et al., 1970) are properly accounted for by the deep structure (Ocola and Meyer, 1973). Both cross sections show crustal thicknesses of 76 km under the altiplano and infer a thickness of 40 km under the Amazon Basin.

Using phase and group velocities in a study of the dispersion of earthquake generated Love and Rayleigh waves sensed by an eight station array on the coast and altiplano, James (1971a) derives a crustal model that indicates a crust over 70 km thick under the western cordillera, but only 50 to 55 km thick under the eastern cordillera on the Brazilian side of the altiplano. Ocola et al., (1971) states that this seems to be an underestimate of the thickness, and that due to insensitivities in James' (1971a) model, the crustal thickness can be increased without significantly affecting the theoretical dispersion curve.

Wilson (1963 and 1965) and Morgan (1971) suggest that aseismic ridges may indicate relative plate motion over a hot spot in the upper
mantle. Noting the topographic trends and aseismicity of the ridges, Herron (1972) suggests that the Cocos, Tehuantepec, and Nazca Ridges may indicate such hot spots, but that if so, the Nazca Ridge must have formed prior to ten million years ago. Mammerickx et al., (1975) inferred from a pattern of changes in trend observed along several fracture zones on the Nazca Plate that the Nazca Ridge may be an extension of the Sala y Gomez Ridge. Magnetic anomalies support but bathymetric features do not support this inference. Expedition Downwind (Fisher, 1958) noted that between 700 and 1000 km offshore the Nazca Ridge is larger, asymmetric, and steeper on the southeast side. However, the topographic expression changes abruptly about 500 km offshore, and remains fairly uniform from there to the Peru-Chile Trench.

A trackline through the region between the Nazca Ridge and the Sala y Gomez Ridge by the R/V Oceanographer crossed two seamounts near 25° S. Lat., 88° 40' W. Lon. (Rea, personal communication, 1973). The ocean floor shoaled to 320 m and the free-air gravity anomaly was at least +85 mgl. Unfortunately, the gravity meter output over-ranged, and the maximum anomaly was not recorded.

Earthquake seismological studies by Benioff (1954) noted the earthquake foci (hypocenters) formed zones of seismic activity dipping landward from trenches under the adjacent continent. Stauder (1975)
projected earthquake hypocenters onto cross sections and observed that the Benioff zone north of the Nazca Ridge is shallower than south of the Nazca Ridge, and that fault plane solutions indicate underthrusting. James (1971b) noted that upper mantle structure and seismicity shows the Nazca Plate underthrusting South America is about 50 km thick, and that the overriding plate is 200 to 300 km thick. However, Oliver (1974) points out that the deep earthquakes are within the descending slabs rather than along a slip plane on the top surface.

Generally plate boundaries and continental margins do not coincide, but where they do "huge shocks" such as the 1960 Chile and 1964 Alaska earthquakes are observed (Oliver, 1974). Kelleher (1972) notes a number of earthquakes of Richter Magnitude greater than 8.0 along Western South America. One of the earthquakes near the town of Nazca in 1942 (M 8.6) was followed by a series of aftershocks offshore near the coast opposite the Nazca Ridge.

Oliver (1974) stated that focal mechanisms show clear evidence of extension near the upper surface of oceanic plates as they bend down near trenches. The sediment wedge above the Benioff zone landward from the trench shows both thrust faulting and strike slip faulting. Compressive stresses are aligned perpendicular to the margin in convergent zones (Oliver, 1974).

Pre-Cambrian rocks are seen extensively on the coast between the Paracas Peninsula and about 17° S. Lat. They are chiefly
granodioritic and granitic in character (Steinmann, 1930; Masias, 1975). Upper Paleozoic, but Pre-Mesozoic, rocks make up much of the remaining outcroppings (Jenks, 1948; Anonymous, 1969; and Masias, 1975). The onshore Pisco Basin contains upper and lower Tertiary sediments (Petersen, 1954; Bellido, 1969; Sanz, 1973; and Masias, 1975). Mesozoic sedimentary and volcanic rocks distributed along the coast include submarine pillow lavas, tuffs and agglomerates identified mainly as andesites and basalts corresponding to upper Triassic to upper Jurassic units. Cretaceous geosynclinal deposits crop out extensively in the western Andes, but Plutonic rocks form the Andean batholith (Hosmer, 1959; Masias, 1975). The Abancay Deflection trends northeast from about 13° S. Lat. on the coast and the Arica-Santa Cruz Deflection trends approximately parallel to it 5 degrees to the south (Masias, 1975). The region between these two features is itself sometimes called the Abancay Deflection, and is onshore from the Nazca Ridge province described by Getts and Rose (1975). The continental margin is very narrow offshore, and the coastal mountains described above are offset about 100 km landward north of the Abancay Deflection at 13° S. Lat.

The widest portion of the continental slope along the Peruvian coast lies between 11° and 14° S. Lat. It is 120 to 140 km wide through this region and narrows to 50 km opposite the Nazca Ridge. The continental shelf is widest between 7° and 10° S. Lat., narrowing
to about 30 km between 12° and 14° 40' S. Lat. except for the Paracas Bay where it is 80 km wide. Farther south it continues to narrow, reaching a minimum width of 5 km at 16° 30' S. Lat. South of 16° 30' S. Lat. it begins to widen slightly, but it remains relatively narrow far south of Peru.

A series of shelf and slope basins mark the margin between 12° and 18° S. Lat. The Lima Basin (Masias, 1975) extends from near 10° S. Lat. south to about 14° S. Lat. This is the basin Hayes (1966 and 1974) refers to as the extension of the Bolivar geosyncline or "its counterpart to the south." The Pisco Basin is on the shelf and on shore between 13° and 14° S. Lat. There is a very small shelf basin near the coast at 15° S. Lat. The Mollendo Basin extends from about 16° 30' S. Lat. south to Antofagasta (Coulbourn and Moberly, 1975) but with its largest portion near Mollendo. This basin is called the Arequipa Basin by Masias (1975). Masias (1975) describes possible migration of these basins, landward or seaward, as a function of uplift rates of the basement under the shelf edge and the upper slope break.

A break, or bench edge, on the continental slope near its upper end is called an upper slope break and they are widespread. Karig and Sharman (1975) observe one on most of the western Pacific trench crossings, and Prince and Kulm (1975) observe one on many of the Peru-Chile Trench crossings between 6° and 10° S. Lat. The upper
slope break is interpreted as caused by uplift, and where observed it controls an upper slope basin on its landward side.

The Nazca Ridge is normal faulted at its northeast end where it intersects the trench, and substantial amounts of calcium carbonate were found in the pelagic sediments on both sides of the trench (Kulm et al., 1974). Because the sediments were found below the 4000 m level, below which calcium carbonate usually dissolves, and because similar sediments are found in abundance on the shallower portions of the Nazca Ridge, this is taken as direct evidence for faulting and convergence leading to accretion on the margin (Kulm et al., 1974). Furthermore, similar sediments were found over 1800 m above the trench floor and 100 km northwest of the present intersection of the axis of the Nazca Ridge with the Peru Trench (Rosato, 1974), indicating the expected southeastward migration of the ridge relative to the margin due to non-normal relative plate motion (Minster et al., 1974).

Goebel (1974) and Hussong et al., (1975a) report thrust faulting on the Nazca plate seaward from the trench based on interpretation of sonobuoy refraction measurements. The two-ship refraction lines 1-2 and 2-3 in Figure 4 (Hussong et al., 1973) lie across the Mendana fracture zone (Mammerickx et al., 1975) but Hussong et al. (1975b) states that no unusual crustal structure due to the fracture zone is observed.

Based on the interpretation of seismic reflection records and radiologic dating of cored turbidite sediments, Kulm et al., (1973)
and Prince and Kulm (1975) report uplift of ruptured, block faulted basalts in the trench at rates as high as 14 to 22 cm/yr. They also suggest imbricate thrusting on the lower slope, and uplift under the upper slope break. Seeley et al. (1974) postulate a thrust fault and folding process as a trench slope model that is similar to the imbricate thrusting suggested above. Hence Prince and Kulm (1975) are suggesting a model where pelagic sediments are accreting onto the margin, whereas Hussong et al. (1975b) argue for erosion of terrigenous sediments from the margin by the underthrusting oceanic plate (see Scholl et al., 1970). Masais (1975) concludes that the Peruvian margin is growing seaward by accretion, and that continental erosion is not necessary.

New Data

In addition to the gravity data discussed in detail in the next section, new data presented here include a bathymetry map, 4 seismic reflection profiles, and a two-ship seismic refraction line. The bathymetry map of the margin of southern Peru was compiled from the work of Masias (1975) and Prince and Kulm (1975) as well as this paper. The trackline map in Figure 1 shows most of the control for the map, but was supplemented in places by HIG tracklines. The map was contoured by Gorden Ness and Roger Prince of the School of Oceanography, Oregon State University. The seismic reflection profiles are from portions of the same tracklines from which the
gravity and bathymetry data were taken for the crustal and subcrustal cross sections discussed in Section III. Seismic refraction line 3'–4 shown in Figure 4 was shot by OSU and HIG in 1974 and the data reduced and analyzed by D. Hussong and S. Johnson (personal communication, 1975).

Transducers operating at 3.5 and 12.5 kHz provided the signal for precision depth recording, and two 40 in$^3$ air guns supplied the high energy seismic waves of low frequency for reflection profiling. A multiple hydrophone streamer trailing the ship detected the reflected waves, and the amplified, band-pass filtered signal was recorded on a single channel EPC recorder with a 4 sec. sweep.

For the two-ship seismic refraction line 3'–4, the R/V Yaquina recorded at station 3' as the R/V Kana Keoki dropped chemical explosives while sailing northeast along the crest of the Nazca Ridge. The R/V Kana Keoki stopped about 120 km away at station 4 and recorded as the R/V Yaquina dropped explosives while sailing toward her along the same line.

Satellite fixes together with the log of course and speed changes are processed by a program (Gemperle, 1974) that yields navigation parameters with an estimated uncertainty of ±0.2 km in position, ±1° in heading, and ±0.1 knot in speed. Accurate navigation reduces the uncertainty in the Eotvos correction applied to gravity measurements recorded while moving on the spherical surface of the earth.
II. THE FREE-AIR GRAVITY ANOMALY MAP
CONTINENTAL MARGIN OF SOUTHERN PERU

The trackline map in Figure 1 shows the location of gravity measurements used in preparing the free-air gravity anomaly map shown in Figure 2. Oregon State University personnel made measurements in the area during the Yaquina Long Cruise 1971-1972 (YALOC '71) leg 6 (Callao, Peru to Callao, Peru) and YALOC '73 legs 6 (Valparaiso, Chile to Callao, Peru) and 7 (Callao, Peru to Callao, Peru). Additional data are submarine pendulum stations obtained by the USS Conger in 1947 (Worzel, 1965), surface ship gravity measurements made by the R/V Oceanographer during 1967 (Sea Gravity Data, Project Opr. 476, NOAA), and land gravity measurements made in Peru from 1958 to 1963 and compiled by the Instituto Geofisico del Peru. The land gravity data was obtained from the Defense Mapping Agency Aerospace Center in St. Louis, Mo.

The data collection system aboard the R/V Yaquina included LaCoste and Romberg surface ship gravity meter S-42 which includes a stable platform, a digital data acquisition system and an analog recording system. On-board signal processing used three 20 second analog filters, a symmetrical digital filter with a 5 minute time delay for the digital system and an analog filter with a 3 minute delay for the recorder. Final processing removed these time delays so data
Figure 1. Trackline map showing the location of the gravity measurements used to generate a free-air anomaly map and constrain crustal cross sections. The bathymetric contours are in meters.
obtained from the digital system in YALOC '71 was equivalent to data
obtained from the analog system in YALOC '73.

An absolute reference for the ship's gravity meter was obtained
in port by using a portable land gravity meter to measure the differ-
ence between the acceleration of gravity at the ship's meter and at a
nearby International Gravity Base Station. YALOC '71 and '73 data
off Peru are referenced to station WH 1068 (Woollard and Rose, 1963)
in Callao, Peru, but the gravity value given by Woollard of 978.3127
gals (1 gal = 1 cm/sec²) was adjusted to 978.2982 gals. This change
is made to adopt the 1967 convention wherein the accepted gravity
value on a pier in the basement of the Commerce Building, Wash-
ington, D.C. (to which Woollard's work is referenced) is reduced by 14.5
mgl from 980.1188 gals to 980.10429 gals.

The free-air gravity anomaly was calculated using the equation
FAA = observed gravity + free-air correction - Theoretical Gravity.
FAA is the free-air anomaly, observed gravity is the locally meas-
ured gravity value, and the free-air correction corrects for changes
in gravity due to elevation differences. The free-air correction used
was 0.3086 mgl/meter, but second order terms were included when
they exceeded 0.1 mgl (i.e. for elevations greater than 1.17 km).
Theoretical Gravity was computed using the 1967 Gravity Formula
g = 978031.85 \left(1 + 0.005278895 \sin² \phi + 0.000023462 \sin⁴ \phi\right) \text{mgl}, \text{ where}
\phi \text{ is the latitude of the measurement.}
The gravity meter readings, referenced to base stations at each port of call, and the meter calibration curve supplied by LaCoste and Romberg allow calculation of instrumental drift. The gravity meter drift was 4.1, 6.4, and 1.3 mgl for YALOC '71 leg 6 and YALOC '73 legs 6 and 7 respectively. Fortunately YALOC '73 leg 7 comprises 59% of the trackline distance of the R/V Yaquina in the gravity survey region - i.e. 7852 km of a total 13403 km. Furthermore, leg 7 includes 17 of the 23 trench crossings and its trackline nearly surrounds the tracklines of the other two legs, thereby providing the gravity data along the survey area boundary.

The gravity meter drift of 6.4 mgl for YALOC '73 leg 6 is high, but was measured over a 22 day cruise which started in Valparaiso, Chile, and only the last 3 days were within the survey area. Data used for the gravity map are referenced to the base station in Callao, Peru, so it is probable that meter drift while in the survey area was less than 2 mgl. This leg accounts for 9% of the trackline distance and 1 trench crossing in the survey region.

YALOC '71 leg 6, with 4.1 mgl drift, includes 32% of the trackline distance and 5 of the 23 trench crossings. There is some evidence from crossing point errors (differences between measured anomalies at points where tracklines intersect) that most of the drift occurred late in the cruise. Therefore, gravity data from this leg were referenced to the base station observation made at the start of
the cruise in Callao, Peru.

The estimated RMS uncertainty for the free-air gravity anomaly map is 4 mgl based on careful measurement of the crossing point error at 12 intersections, and comparing nearly all other intersections. With only a few exceptions, the contour lines are not smoothed through the tracklines, but cross each one at the appropriate anomaly value. Observation of the linearity of the contour lines along the seaward side of the trench axis, where there are 23 trackline crossings, qualitatively confirms the uniformity of the data.

Data density along the ship's trackline is approximately one gravity value each 1.4 km. This results from a sampling interval of 5 minutes at a ship speed of 9 knots, and yields data sufficient to define the field even in regions where the gravity anomaly gradient is large. Twenty three crossings of the trench axis occur between 12° and 18° S. Lat. along a segment of the trench about 900 km long. In the region between the trench axis and the coast the trackline density is sufficient to resolve features 20 to 30 km or less in horizontal dimension.

The profile index map in Figure 4 shows the approximate position of the northeast end of the Nazca Ridge, a topographic feature which extends over 1000 km to the southwest of the Peru Trench. The 3000 and 4000 meter bathymetric contours on the trackline map (Figure 1) show its location more precisely. Over the Nazca Ridge
and the abyssal sea floor southwest of the trench, tracklines are more widely separated and resolution is generally limited to features greater than 100 km in horizontal dimension. The shape of the gravity anomalies in this region are constrained by limited data. The most significant observation is the absence of an anomaly pattern coincident with the Nazca Ridge. In contrast, free-air gravity anomalies over the Mendocino Ridge (Dehlinger et al., 1967), the Tehuantepec Ridge (Woodcock, 1975), and the Cocos Ridge (Barday, 1974), for example, clearly indicate the presence of ridges that are smaller than the Nazca Ridge.

The gravity anomaly map, in the region southwest of the trench, shows several small gravity highs, corresponding to seamounts; a larger +20 mgl anomaly over the northeast end of the Nazca Ridge; and what may be a general offset toward the northwest of the contours near the trench. The zero mgl contour near 14° S. Lat., 79° W. Lon., and the +10 and +20 mgl contours to the southeast partially enclosed by it, and the +20 mgl contour near 18° S. Lat., 75° W. Lon. illustrate this offset. The +20 mgl anomaly over the northeast end of the Nazca Ridge is probably due to the higher bathymetry there, but crustal thinning may also contribute. Crustal thinning is observed near the trench south of the Nazca Ridge, but not north of it (see Figures 5 and 8).

The predominant anomaly on the gravity map is the negative
Figure 2. Free-air gravity anomaly map. The dashed lines indicate inferred contours. The estimated RMS uncertainty is ±4 mgl.
Figure 3. Bathymetry map. Contour interval is 200 m. Depths were corrected using zone 42 of Matthew's tables.
anomaly associated with the Peru-Chile Trench. Along the axis of the gravity anomaly minimum the highest value is -110 mgl near 13° 45' S. Lat. and the lowest value is -220 mgl at 17° S. Lat. This axis is offset landward 5 to 15 km from the bathymetric axis of the trench. There is also a 200 km offset toward the northwest parallel to the trench between the highest bathymetric point on the trench axis near 15° 15' S. Lat. (Figure 3) and the highest gravity anomaly value at 13° 45' S. Lat. The highest point on the trench axis is about 4900 m below sea level and occurs near the intersection of the Nazca Ridge axis and the Peru Trench. The free-air gravity anomaly corresponding to this point is -163 mgl. The ocean depth corresponding to the previously described -110 mgl anomaly is approximately 5500 m. Hence along this 200 km offset, from southeast to northwest, the gravity value increases 53 mgl while the sea deepens about 600 m.

A sharp break in the -100 mgl contour on the landward side of the trench just south of 13° 30' S. Lat. coincides with a very similar break in the 3600 m bathymetric contour. A series of four relative gravity lows along the minimum anomaly axis, beginning with the -180 mgl low at 15° 30' S. Lat. and extending southeast to adjacent -190, -220, and -210 mgl lows near 17° 30' S. Lat. generally coincide with bathymetric changes through this region.

The steep continental slope, rising from the trench axis 5 to 7 km deep, to a depth of a few hundred meters, over a horizontal
distance of less than 100 km causes the dominant effect on the gravity anomaly field northeast of the trench. Were it not for the partially compensating effect of the relatively low density, very thick continental crust under the Andes Mountains, the high density contrast across the sea bottom interface combined with this steep slope would produce an increase of 350 to 450 mgl in the gravity anomaly from the trench to the coast. That the change is more nearly 150 to 250 mgl reveals the effect of the lower crust and upper mantle. Thus it is possible for mass changes in the lower crust and upper mantle to cause relative gravity lows on the continental margin in regions not dominated by a steep slope. Hence where both a thickening of low density material in the upper structure and a large area of general flattening of the slope occur, such as a perched basin on the slope or a shelf basin, relatively large gravity lows are produced.

Two prominent relative gravity lows on the margin are those associated with the Pisco Basin on the shelf at 13° 25' S. Lat. near the coast north of Pisco, Peru, and the Mollendo Basin on the slope about 17° 10' S. Lat. near Mollendo, Peru. Section III describes gravity models of the upper crust of these basins shown in Figures 11 and 13.

The -90 mgl low near 13° 15' S. Lat. on the slope and the -30 mgl low very near the coast on the shelf near 15° S. Lat. are similar features. The shelf basin near 15° S. Lat. produces a gravity
anomaly of about 30 mgl in amplitude but without the outer shelf high as at Pisco. Comparison with the Pisco Basin anomaly suggests a depth to basement of about 1 km for this basin.

The slope basin near 13° 15' S. Lat. differs from the Mollendo Basin in that it is more elongate both gravimetrically and bathymetrically. It is 10 to 20% smaller in area and in gravity anomaly amplitude, and has about 50% less bathymetric relief. The bathymetric high just seaward from it produces the -50 mgl relative high seen on the gravity map seaward of the -90 mgl low. A similar ridge seaward and south of the Mollendo Basin probably would produce a similar relative high, but there is no gravity measurement over it. Hence comparison of the -90 mgl anomaly with the Mollendo Basin anomaly, and consideration of the larger regional gradient due to deep structure in the north (Section III), suggests there is approximately 1 km of sediment in the basin. Wide angle seismic reflection data (Johnson et al., 1975) confirms this estimate.

A coastal gravity high of +20 to +50 mgl extends from Mollendo to Lima except for two gaps, one between 14° and 15° S. Lat. where there is a shelf basin but no coastal land gravity data (Figure 1), and the other for the extended Pisco Basin. The Generalized Geology Map of Peru (Anonymous, 1969) shows pre-Cambrian rocks outcropping along the coast, including gneisses and granodiorites, and also andesites and basalts of Mesozoic age. It is difficult
to differentiate between the densities of these rocks without additional field data. However, the high density contrast between these rocks and any overlying sediments allows approximate calculation of sediment thickness from gravity measurements.

The gravity anomalies show this coast structural high extends nearly 100 km out to sea from the Paracas Peninsula southwest of Pisco, following the shelf edge to approximately 13° S. Lat. The +20 mgl high directly west of the Pisco Basin low is the most prominent gravity anomaly along this extension. There is a clear discontinuity near 13° S. Lat. where the coastal and shelf highs appear to be offset about 50 km to the northeast.

The gravity anomaly high at the north edge of the map near Lima which extends out on the shelf is wider and has greater amplitude than any other positive anomaly on the map. More data to the north are necessary to postulate a cause for this gravity high.

The wide zero mgl relative gravity high off the coast near 14° 30' S. Lat. coincides with a slightly wider shelf in that area, and suggests high density rocks lie near the surface under the shelf edge and dip steeply under the slope. The contorted contours seen in the region of 16° S. Lat., 74° 30' W. Lon. probably are caused by small basins in the region.
III. CRUSTAL AND SUBCRUSTAL CROSS SECTIONS

Geophysical Constraints

Gravity model cross sections postulate a two-dimensional mass distribution for the crust and upper mantle which produces the gravity anomalies observed along a profile normal to the known or presumed structure of interest. Surface geology, seismic refraction and reflection, bathymetric, and land elevation data further constrain the proposed structure. The vertical component of gravity at field points on the model was computed using the line integral method of Talwani (Hubbert, 1948, and Talwani et al., 1959) as adapted by Gemperle (1970 and 1975).

The models used in computation have uniform depth throughout, but confine elevations above sea level and lateral density variations to a central region less than a few thousand km wide. Layer thicknesses on each side of the central area are adjusted, if necessary to yield a zero mgl gravity anomaly and to have equal mass columns (total mass per unit area vertically through the model). These adjusted layers are extended ten million km to each side of the central area to isolate edge effects and approximate an infinite slab. Hence subtraction of the gravity value calculated on the surface of the model at either side, far removed from its center or edges, from that calculated at a point in the central region yields the free-air gravity anomaly at that central point.
Calculating the free-air gravity anomaly at field points on the surface of the model allows mass at elevations higher than the field points to influence the result and produces a two-dimensional terrain corrected anomaly field. It also avoids distortion in the calculated anomaly profile that ordinarily results from computing the gravity field at sea level, i.e., at field points closer to sources than the original land gravity stations.

The profile index map in Figure 4 shows the location of 5 profiles and 7 seismic refraction lines. Scripps' Expedition Downwind, 1957-1958, provided two-ship refraction lines DW 22 (Shor et al., 1970) and DW 23 (Fisher and Raitt, 1962). The Nazca Plate Project conducted jointly by the Hawaii Institute of Geophysics and Oregon State University supplied two-ship refraction lines 1-2, 2-3, (Nazca Plate Project Progress Report, 1973), and 3'-4 (Hussong and Johnson, personal communication, 1975). Land refraction includes a reversed line from the Carnegie Institute's Peru-Bolivia Altiplano Refraction of 1968 (Ocola et al., 1971) and the unreversed line 890 (McConnell and McTaggart-Cowan, 1963) from Seismic Crustal Studies during the IGY (Woollard, 1960).

The crustal and subcrustal cross sections (Figures 5, 7, and 8) show the location of the depth control indicated by these refraction lines. Table I shows the compressional wave velocities measured in each of the layers for the 7 lines. These velocities, together
Figure 4. Profile index map. Dark lines indicate the traces of the crustal cross sections. Light lines indicate the location of seismic refraction lines used to constrain the cross sections.
Table I. Seismic Velocities and Layer Thickness

<table>
<thead>
<tr>
<th>Refraction Line</th>
<th>Water</th>
<th>Sediment</th>
<th>Upper Crust</th>
<th>Lower Crust</th>
<th>Mantle</th>
<th>Total T</th>
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<tr>
<td>(Station Position)</td>
<td>V</td>
<td>T</td>
<td>V</td>
<td>T</td>
<td>V</td>
<td>T</td>
</tr>
<tr>
<td>1-2 (1)</td>
<td>1.5</td>
<td>4.22</td>
<td>1.7*</td>
<td>0.17</td>
<td>4.23</td>
<td>0.50</td>
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<tr>
<td>1-2 (2)</td>
<td>1.5</td>
<td>4.53</td>
<td>1.7*</td>
<td>0.14</td>
<td>4.23</td>
<td>0.40</td>
</tr>
<tr>
<td>2-3 (2)</td>
<td>1.5</td>
<td>4.53</td>
<td>1.7*</td>
<td>0.14</td>
<td>4.23</td>
<td>0.46</td>
</tr>
<tr>
<td>2-3 (3)</td>
<td>1.5</td>
<td>4.40</td>
<td>1.7*</td>
<td>0.20</td>
<td>4.23</td>
<td>0.44</td>
</tr>
<tr>
<td>3'-4 (3')</td>
<td>1.5</td>
<td>3.00</td>
<td>1.7*</td>
<td>0.24</td>
<td>3.65</td>
<td>0.78</td>
</tr>
<tr>
<td>3'-4 (4)</td>
<td>1.5</td>
<td>2.95</td>
<td>1.7*</td>
<td>0.21</td>
<td>3.65</td>
<td>0.99</td>
</tr>
<tr>
<td>DW 22 (C)</td>
<td>1.501</td>
<td>4.52</td>
<td>2.15*</td>
<td>0.11</td>
<td>5.22*</td>
<td>0.81</td>
</tr>
<tr>
<td>DW 23 (C)</td>
<td>1.501</td>
<td>4.47</td>
<td>2.15*</td>
<td>0.30</td>
<td>5.24</td>
<td>1.34</td>
</tr>
<tr>
<td>890 (S)</td>
<td>5.3</td>
<td>4.1</td>
<td>6.2</td>
<td>21.2</td>
<td>6.7</td>
<td>26.4</td>
</tr>
<tr>
<td>Carnegie (S)</td>
<td>4.5</td>
<td>3.7</td>
<td>5.7</td>
<td>17.1</td>
<td>6.8</td>
<td>50.</td>
</tr>
</tbody>
</table>

V = Velocity in km/sec  
(C) = Center of line  
T = Thickness in km  
(S) = Shot point  
* = Assumed velocity  
+ = Velocity poorly defined

Note: Data from lines 1-2 and 2-3 was averaged (see text) and data from line 3'-4 was taken from its northeast end (station 4).

Lines 1-2 and 2-3 from Nazca Plate Progress Report (1973)  
Line 3'-4 from Hussong and Johnson (Personal Communication, 1975)  
Lines DW 22 and DW 23 from Shor (1969)  
Line 890 from McConnell and McTaggart-Cowan (1963)  
Line Carnegie from Ocola and Meyer (1971)
with empirical curves for density versus compressional wave velocity (Nafe and Drake, 1961, and Ludwig et al., 1970), yield the approximate density for each of the respective layers.

The Mollendo Cross Section

The Mollendo crustal and subcrustal cross section (Figure 5) lies along the Mollendo Profile shown in Figure 4. The dashed line extensions indicate the portion of the profile beyond the region of gravity control. Refraction control from DW 22 is projected normal to the profile onto its southwest extension. The northeast extension shows where the layers in the model were adjusted to balance the sides of the model section. Refraction line 890 is projected orthogonally onto the profile from its midpoint, and the Carnegie line intersects the profile on the altiplano near km 1185 on the horizontal scale of the Mollendo Section (Figure 5).

A gap about 85 km long occurs in the gravity data about 125 km seaward from the trench. The anomaly through this region is inferred from the gravity anomaly map. Southwest of the gap, between km 300 and km 600, gravity and bathymetry data is projected normally onto the profile from the trackline which extends between 19° 45' S. Lat., 77° 15' W. Lon. and 18° 15' S. Lat., 75° 15' W. Lon. (Figure 1). The profile crosses the trench nearly coincident with the trackline lying between 18° S. Lat., 74° 10' W. Lon. and 16° 30' S. Lat., 73° 15' W. Lon.
Figure 5. Mollendo cross section. The vertical exaggeration is 10:1.
Land gravity data (see Figure 1) along roads which cross the trace of the section profile near the coast, on the southwest side of the Andes at km 965, on the altiplano between Lake Titicaca and Cuzco near km 1200, and projected from a nearby road onto the section at km 1090 provide the gravity control through the Andes. Two isolated land gravity stations in the Amazon Basin (not shown on Figure 1) are close to the profile and project onto it at km 1320 and km 1560.

Except at land gravity stations, elevations were obtained from Air Force charts ONC N-25, 2nd edition, and ONC P-26, 4th edition, which are contoured at 1000 foot intervals over most of the needed area. Using the exact elevation given for a particular land station chosen for gravity control eliminated any error of approximately 0.1 mgl/meter that would arise from an elevation difference between the model cross section and the gravity station.

The coastal geology previously discussed (Section II) requires extending the 2.75 g/cm$^3$ layer upward to the surface near the coast. However, the gravity anomaly amplitude is so high that the crust must remain relatively thin through this region.

The Mohorovicic Discontinuity (Moho), indicated by the upper boundary on the 3.3 g/cm$^3$ upper mantle layer, rises from 10.5 to 8.5 km below sea level between km 300 and km 730, near the trench, resulting in crustal thinning toward the trench. From the region near
the trench the Moho dips at about 5° and reaches a depth of 26.5 km below sea level approximately 50 km inland. There the dip of the Moho steepens to about 26°. Seismic refraction shows the Moho is nearly 60 km below sea level about 100 km inland, and reaches its greatest depth of 67 km below sea level (over 70 km below the surface) at km 1190. From there toward the northeast the crust thins, with the Moho reaching a depth of 33 km below sea level near km 1350, under the northeastern flank of the Andes. However, while the structure shown between km 1200 and km 1600 is consistent with the gravity data, it should be noted that no seismic refraction information is available for this region. The gravity minimum of -75 mgl on the lowlands near the Andes is probably due to the thick, relatively low density crust under the Andes. A negative anomaly extends along this flank of the Andes from at least 10° to 25° S. Lat., and probably farther (Grow and Bowin, 1975).

The apparent thinning of the 2.9 g/cm³ layer immediately above the Moho, between 50 and 100 km inland, is an artifact of the 10:1 vertical exaggeration on Figure 5. Figure 10 shows the Mollendo and Pisco cross sections at a vertical exaggeration of 1:1 so the model structure is seen in proper perspective. The 2.9 g/cm³ layer is maintained at a thickness of 4.5 km from just landward of the trench to about 100 km inland. This makes the gravity field very sensitive to changes in the depth to Moho in this region and at least 50 km inland.
because the density contrast between the 2.75 g/cm\(^3\) layer and the 3.30 g/cm\(^3\) layer is 0.55 g/cm\(^3\). Hence the dip of the Moho through this region, and particularly the position where the dip changes from about 6° to about 26° (at km 935) is well controlled by the gravity data.

The Mollendo section shows no thin, very low density sediment layer on the sea floor because the seismic reflection profile shows such sediments to be generally less than a few tens of meters. The contribution to the gravity field from such a layer would be less than 1 mgl. The density of the upper layer seaward of the trench is reduced from 2.6 to 2.4 g/cm\(^3\) on the seaward wall of the trench.

Figure 6 shows the seismic reflection profile along the Mollendo profile. The presence of hyperbolas on the seaward wall of the trench indicate a generally faulted or broken up structure that would likely reflect a lower average density.

The relatively low density layers of 2.0 and 2.5 g/cm\(^3\) are interpreted as accreted material. The seismic reflection profile in Figure 6 shows little sedimentary structure that would be interpreted as recent. These layers are probably dewatered, compacted oceanic and terrigenous sediments. However, upslope the reflection profile does show horizontal sediment layering in the basin just landward of the first bench near km 774, and seaward dipping layers near the end of the profile at km 832. Two valleys, approximately 300 to 400 m deep, are observable on the reflection profile near km 799 and
Figure 6. Continental margin portion of the Mollendo seismic reflection profile. The horizontal scale corresponds to the scale on the Mollendo section in Figure 5.
km 830. The irregular topography of the slope shown in Figure 6 continues landward beyond the end of the seismic reflection record. The bathymetry profile in Figure 5 shows two additional valleys on the upper slope near km 845 and km 855.

The Nazca Ridge Cross Section

The index map in Figure 4 shows the trace of the Nazca Ridge cross section (Figure 7) and the location of the constraining seismic refraction lines 1-2, 2-3, and 3'-4. Measurements along the track-line in Figure 1 between 15° 45' S. Lat., 79° 30' W. Lon., and 18° S. Lat., 77° W. Lon. which traverses the ridge normal to its axis about 270 km southwest of the Peru Trench provide the gravity and bathymetry data for this section. Seismic refraction line 3'-4 oriented approximately along the ridge crest nearly intersects the section profile. Results from this line indicate northeast dipping layers (see Table I), so depth control for the section is taken from the northeast end of the refraction line.

Refraction control for the northwest end of the Nazca Ridge section is taken from lines 1-2 and 2-3 even though they are farther from the ridge than DW 23. These lines were selected because they lie farther from the trench axis than DW 23, so structure there should be less affected by tectonic activity in the trench. The seismic velocities and depths measured at 1-2 and 2-3 are averaged for each
Figure 7. Nazca Ridge cross section. The vertical exaggeration is 10:1.
of the layers observed, and the results projected onto the northwest extension of the section.

Structural control for the southeast extension of the Nazca Ridge section is taken from the Mollendo cross section. These two cross sections intersect near km 800 on the Nazca Ridge section and km 460 on the Mollendo section.

As previously stated in Section II, the free-air gravity anomaly pattern in the region of the Nazca Ridge gives little indication of a large topographic feature (see Figures 2 and 3). Yet the density contrast between the sea floor and the overlying water combined with the 1.2 and 1.7 km topographic relief of the ridge would, if uncompensated, cause gravity anomalies of +75 to +100 mgl over the highest parts of the ridge. Hence the gravity anomalies indicate a generally lower density and/or thicker crust under the Nazca Ridge compared with the surrounding area. Seismic refraction data from line 3'-4 supports this, indicating a substantially thicker crust and slightly lower crustal densities than are found on either side of the ridge.

Figure 7 shows dashed line interfaces in the crust on each side of the ridge indicating the regions where densities are adjusted because slightly lower seismic refraction velocities are measured under the ridge. Layer densities are reduced 0.03 to 0.04 g/cm$^3$ under the ridge relative to densities to the northwest.

Thickening of the lower crust is most pronounced, but it occurs
in all layers. Depth to Moho increases from 10.5 km below sea level on the northeast side of the ridge to 18 km under the center of the ridge, rising again to 9.7 km southwest of the ridge. The simple shape shown in Figure 7 for the Moho under the ridge is a best approximation for that interface; any more detailed structure would be speculative.

The 1.7 g/cm$^3$ sediment cover overlying the ridge thickens from near zero on each side to about 300 m in the middle. This variation is caused by dissolution of calcium carbonate, a major constituent of the sediment in this area, at depths greater than 4000 m (Kulm et al., 1974, and Rosato, 1974). The ocean depth over the top of the ridge varies between 2600 to 2900 m, but increases to 4700 m on each side.

The upper crust shows more structural variation on the south-east flank of the ridge which may indicate faulting has occurred in this region. More complete data on the ridge and its flanks, including nearby refraction, are necessary before identifying such a pattern with certainty (see Mammerickx et al., 1975).

The Pisco Cross Section

Figure 4 shows the trace of the Pisco cross section and the position of seismic refraction line DW 23 used to constrain this section model. The dashed line extensions show that portion of the
Figure 8. Pisco cross section. The vertical exaggeration is 10:1.
section outside the region of gravity control. This includes all of the northeast flank of the Andes beyond Huancayo, Peru, and, to the southwest, the intersection with the extension of the Nazca Ridge section. The structure of these two sections have equivalent mass columns where they intersect. The northwest side of the ridge section shows a two layer upper crust and a two layer lower crust. The upper crustal layers and lower crustal layers are independently combined (thicknesses summed and densities averaged over depth) to yield the single upper crustal layer and single lower crustal layer shown at the seaward end of the Pisco section (Figure 8).

Gravity and bathymetry profiles for the seaward portion of the Pisco section are from measurements along two tracklines (Figure 1). One trackline runs from near 15° S. Lat., 79° W. Lon. northeast across the trench and turns north. The second trackline is southeast of the first and runs parallel to it across the trench, but continues northeast to a point near the coast at 13° 15' S. Lat. The data from both tracklines are similar where they parallel each other, and nearly identical on the seaward trench wall. The first trackline provides data southwest of the trench and the second trackline provides data between the trench and the coast.

The structure indicated by DW 23 is adjusted upward about 0.4 km because the ocean depth is about 400 m more shallow where DW 23 projects onto the Pisco section. Refraction lines DW 24 and
DW 25, northeast of DW 23 and not shown on the index map, are not used for control because they are north of the discontinuity observed at 13° S. Lat. This causes uncertainty in the projection of them onto the section, and the adjustments made for the different gravity anomaly field observed north of 13° S. Lat.

There is no land refraction control closer to the Pisco section than that used for the Mollendo section. Hence the densities and approximate layer thicknesses are taken from the Mollendo section, projecting them northwest parallel to the strike of the Andes. The Andes are narrower across the Pisco section being about 250 km wide compared with 450 km wide across the Mollendo section. Earthquake seismology indicates a general narrowing and thinning of the low density root under the Andes to the northwest through this region (James, 1971a). Hence a maximum Moho depth of 60 km below sea level is used for this section, compared with the 67 km shown by refraction for the Mollendo section.

Land gravity data on the seaward flank of the Andes are more closely spaced on the Pisco section than on the Mollendo section. Figure 1 shows gravity stations along a road which extends from the coast northeast into the Andes to approximately 76° W. Lon., and then turns toward the north. However, many of these stations lie in a canyon, and when projected onto the section the elevations reported for each station produce an artificially low profile to the flank of the
Andes. Furthermore, the 2-dimensional terrain correction incorporated into the calculation of gravity values for the model cannot correct for any topographic feature normal to the topography of the cross section. Hence the gravity anomalies reported for each of the stations in the canyon were adjusted by adding an independently calculated 2-dimensional correction for the canyon terrain. Figure 8 shows the resultant gravity profile, and also displays the regional elevation of the Andes, which is different from the elevation of the gravity stations between 25 and 100 km from the coast.

The large block of 3.0 g/cm$^3$ lower crustal material intruding into the 2.75 g/cm$^3$ upper crust in the region under the coast is the result of a combination of geological and gravity constraints. The shallow 2.75 g/cm$^3$ rock under the edge of the continental shelf is the result of the extension of coastal geologic features out under the shelf edge as discussed in Section II. This shallow basement is seen on seismic reflection profiles to the south, such as in Figure 12, and more clearly farther south, but it was not detected on this profile even though the trackline traverses the maximum gravity anomaly observed on the shelf edge. Shoaling of this basement under the shelf edge requires the higher density layers below it to be deeper to fit the observed gravity. This constraint on the lower layers in turn requires the large 3.0 g/cm$^3$ block to extend relatively high under the coastal gravity high. The 2.75 g/cm$^3$ upper crustal layer above
it is already raised to the surface, due to geologic evidence of high density rocks in the coastal region. But it is still necessary to extend the 3.0 g/cm$^3$ block upward as shown to have sufficient mass under the coast to attain the gravity high observed there.

The increased uncertainty in the gravity data inland from the coast, due to uncertainties in terrain corrections discussed above, influences only the landward side of this block. Its size could be reduced if the 3.3 g/cm$^3$ mantle material beneath it were also up-thrust, or the dip of the Moho reduced by lowering the basement under the shelf edge, but an anomalous structure would still be present. Figure 10 shows the block in proper perspective with 1:1 vertical exaggeration. The sides of the block dip at approximately 30°.

The structure under the central Andes can only be approximate as there is only one gravity control point along the profile on the altiplano and no gravity data farther northeast. The structure shown does fit that gravity value, so alternative structures would need to have approximately the same mass column under the Andes as indicated by the section in Figure 8.

The lower oceanic crust is more dense in the Pisco section (3.0 g/cm$^3$) than in the Mollendo section (2.9 g/cm$^3$). This is in agreement with the refraction velocities used for density control of each section. The Pisco section shows no crustal thinning near the trench, unlike the Mollendo section, but this difference is not caused
Figure 9. Continental margin portion of the Pisco seismic reflection profile. The horizontal scale corresponds to the scale on the Pisco section in Figure 8.
Figure 10. Central portions of Mollendo and Pisco sections at a 1:1 vertical exaggeration. See Figures 5 and 8 for detail.
by using the different lower crustal density. No intermediate density layer under the 2.0 g/cm$^3$ layer in the Pisco slope is included because the observed gravity field requires more mass landward of the trench here than under the continental slope on the Mollendo section. The 2.6 g/cm$^3$ upper oceanic crustal layer continues to the trench axis because the seismic reflection profile (Figure 9) shows a relatively smooth wall on the seaward side of the trench.

The Pisco seismic reflection profile also shows a much smoother continental slope than the Mollendo profile. Penetration is deeper, and deformed sediment layers are seen on nearly the entire slope except for the relatively steep portion near the trench axis. The oceanic crust is detected under the slope nearly 10 km beyond the trench. A small perched basin near km 313 shows horizontal sediment fill, and upslope there are sills near km 333 and km 350. A sharp break in the slope occurs near km 372, with sediment fill more than 1 km deep landward from there. Evidence for uplift of this slope break is seen in the upward warping of the sediment layers landward of the break, and the erosion of layers on the edge of the break.

The Pisco and Mollendo Basin Cross Sections

A 3.94 g/cm$^3$ layer inserted below the upper crustal material has no inherent structural significance but substitutes for the lower
crustal and upper mantle mass distributions under these shallow, smaller sections (see Figures 11 and 13). This substitution allows more convenient gravity modeling of the basins to estimate the maximum sedimentary fill, given (or assuming) a complete crustal and subcrustal cross section in the region. The use of 3.94 g/cm$^3$ is arbitrary; the density contrast between it and 2.75 g/cm$^3$ yields about 50 mgl/km for an infinite slab.

Establishing the shape of the 3.94 g/cm$^3$ layer is as follows: first determine the horizontal gradient in the gravity field due only to lower crustal and upper mantle mass distribution in the complete regional section, and then produce that gradient over a shallow section of constant density using a higher density substructure. For the regional section, setting all the upper crustal densities, including the water layer, equal to 2.75 g/cm$^3$ in the vicinity of the continental margin and calculating a gravity profile across this modified region yields a field that is unaffected by any lateral density variations above the lower crust. Restricting the density changes to a portion of the model retains the balance for the end of the regional section. For the shallow section, adjusting the 2.75 to 3.94 g/cm$^3$ interface to produce a field with the same horizontal gradient, before including any other structure, allows subsequent emplacement of a lower density upper structure to fit a specific gravity profile. The negative regional gradient along the continental margin tends to exaggerate
anomalies associated with basins.

The Mollendo section establishes the underlying structure for the Mollendo Basin section, and the Pisco section similarly determines the Pisco Basin section's substructure. However, the magnitude of the horizontal gradient derived from the Pisco section is reduced by 11% because the Pisco Basin profile is not normal to the regional trends in the area, but trends about 27° to the south.

The Pisco Basin

Gravity and bathymetry data for the Pisco Basin section are from the short trackline segment running N 79°E from the 2000 m bathymetric contour at 13° 35' S. Lat. toward the coast. Additional data are from the nearly north-south trackline to the east and coastal land gravity stations. The Pisco Basin trackline intersects the Pisco section trackline near 13° 30' S. Lat., 77° W. Lon., where the crossing point error is about 2 mgl (see Figure 1).

Densities shown in Figure 11 for the Pisco Basin section are the same as for similar layers in the Pisco section. The maximum amplitude of the gravity anomaly over the Pisco Basin is nearly 90 mgl, compared with about 60 mgl on the Pisco section which crosses the basin about 25 km to the north. The model shows a maximum sediment thickness of about 2.2 km (see Zuniga and Travis, 1975), compared with 1.1 km to the north. The sediments in the Pisco
Figure 11. Pisco Basin cross section. The lowest layer produces the horizontal gradient of the regional gravity field. The horizontal scale corresponds approximately with the scale on the Pisco section in Figure 8.
Figure 12. Pisco Basin seismic reflection profile. The horizontal scale and circles are from the Pisco Basin section in Figure 11. The vertical exaggeration is 28:1 from km 350 to km 404 and 14:1 east of km 404.
Basin are thought to be Tertiary overlying Mesozoic (Masais, 1975), and the 2.75 g/cm$^3$ basement is interpreted to be Pre-Cambrian.

The depth to the 2.75 g/cm$^3$ layer at the intersection of the two sections is 3.9 km below sea level on the basin section and 4.05 km below sea level on the Pisco section, shown at km 377 on both sections. This close agreement, constrained only by fitting the model to the observed gravity, demonstrates the validity of this modeling procedure.

The Pisco Basin seismic reflection profile (Figure 12) indicates a generally high basement from perhaps km 405 to km 425, but the lack of penetration in the region near km 420 may be due to poor recording rather than acoustic contrast. Farther offshore the reflection profile shows a sediment layer perhaps 1 km thick between the edge of the shelf and the sharp break occurring on the slope near km 370, where warping and evidence of erosion are seen as in the similar reflection profile to the north (Figure 9). The profile shows only the west side of the Pisco Basin because the trackline does not cross the basin, but turns south at km 432. The interface between the 2.0 and 2.75 g/cm$^3$ layers sketched on the reflection time section uses 1.8 km/sec as the velocity in the upper layer.

The Mollendo Basin

Gravity and bathymetry data for the Mollendo Basin section are
Figure 13. Mollendo Basin cross section. The lowest layer produces the horizontal gradient of the regional gravity field. The horizontal scale corresponds approximately with the Mollendo section in Figure 5.
from the trackline approaching the coast just west of Mollendo. There is only one trench crossing south of this trackline. Land gravity stations along the coast extend gravity control about 10 km past the end of the trackline segment.

Better penetration of seismic waves along the Mollendo Basin profile allows differentiation between upper and lower layers in the basin on this model (Figure 14). The interface between the layers of density 1.8 and 2.2 g/cm³ (Figures 13 and 14) is traceable on the seismic reflection profile from about km 890 to km 920. Wide angle seismic reflection and refraction using sonobuoy receivers (Goebel, 1974, and Johnson et al., 1975) constrain the upper basin seaward to about km 873. This upper basin with its low density sediment fill marks that portion of the Mollendo Basin outlined by the gravity low. The interface sketched on the reflection time section shown in Figure 14 uses a velocity of 1.8 km/sec in the upper layer.

In the basin Cenozoic sediments overlie Mesozoic (Masias, 1975) and the 2.75 g/cm³ basement is interpreted as Pre-Cambrian and/or Mesozoic. The gravity profile coupled with the seismic control constrain the densities in the two upper layers. Increasing these densities requires moving the 2.2 to 2.75 g/cm³ interface downward to unacceptable depths.

The model suggests some differential vertical displacement of the basement which deformed the overlying sediments. This was
Figure 14. Mollendo Basin seismic reflection profile. Horizontal scale and circles are from the Mollendo Basin section in Figure 13.
followed by deposition of the sediments in the low density upper basin layer. The upper basin layer is about 1.4 km thick in its deepest region.
IV. DISCUSSION

The Environmental Data Services Earthquake Data File, listing earthquakes from 1900 through May, 1973, provides worldwide magnitude and hypocenter information. Figure 15 shows earthquake hypocenters which occurred in the study area projected onto the Pisco and Mollendo cross sections. All listed earthquakes within 100 km of the plane of the cross section are projected onto it, and the magnitude of each earthquake is proportional to the area of the circle locating the hypocenter. A plus sign marks the hypocenter if the magnitude was not determined. The Mollendo section has 186 earthquakes plotted on it of which 72 have no magnitude determined, and there are 133 earthquakes plotted on the Pisco section of which 45 have no magnitude determined. The vertical exaggeration of the cross sections is 1:1, so the angles seen are undistorted.

The Benioff zone dips at about 20° on the Pisco cross section, and about 25° on the Mollendo cross section. Figure 15 shows that most of the earthquakes lie in the upper mantle between the trench and the western flank of the Andes. Under the altiplano, which is relatively narrow on the Pisco section and not labeled on it in Figure 15, the number of earthquakes per unit area is less, making it difficult to estimate the dip of the Benioff zone in this region. Nevertheless, there are sufficient earthquakes present to indicate that on the Pisco
Figure 15. Earthquake hypocenter plot. Hypocenters are projected onto the plane of the Pisco and Mollendo sections using all earthquakes within 100 km of the planes. Magnitudes are proportional to the area of the circles. Plus signs indicate that the magnitude is not known.
section the Benioff zone dips less steeply under the altiplano than under the margin, and may become nearly horizontal under the altiplano. This is not the case on the Mollendo section. While the Benioff zone may dip less steeply under the altiplano than between the trench and western flank of the Andes the change is small and the dip under the altiplano is steeper on the Mollendo section than on the Pisco section. The area of concentrated seismic activity seen near the surface of the Pisco section at km 650 corresponds with an isolated zone of activity near 12° S. Lat., 75° W. Lon.

Stauder (1975) made similar hypocenter plots on planes nearly coincident with the planes of the Pisco and Mollendo cross sections. Their traces trend about 6 degrees more easterly than the cross sections, but they intersect the coast within 50 km of where the Pisco and Mollendo profiles intersect the coast in Figure 4. Stauder's plots show more earthquakes because he projected them from a distance of 3 degrees (about 330 km) on each side of the plane.

Stauder's (1975) results indicate a dip of about 30° in the Benioff zone in the region south of the extended axis of the Nazca Ridge, a line trending N 45° E over the crest of the ridge and intersecting the coast at 14° 45' S. Lat. North of that axis a dip of about 20° is indicated under the continental margin and western portion of the Andes, but it becomes less steep to the east, dipping at approximately 3°. Stauder concludes that there is a different subduction process on each
side of the extended axis of the Nazca Ridge. Comparison of his results with those presented here suggests that the change is gradual. His wider projection areas would be less able to discriminate between changes occurring opposite the ridge and across the structural offset observed at 13° S. Lat. Stauder (1975) also solves for the focal mechanisms for 40 earthquakes in Peru and Ecuador, and finds that underthrusting is indicated by the shallow earthquakes under the continental edge and normal faulting and flexure by earthquakes in the oceanic plate to the southwest, but that deep focus earthquakes indicate a vertical segment of the plate under axial compression.

It should be noted that while these hypocenter plots suggest different subduction processes north and south of the Nazca Ridge axis, most of the earthquakes plotted occurred within the last decade and they may not be indicative of the tectonic processes that produced the structure of the region.

Comparison of the Pisco and Mollendo crustal and subcrustal cross sections (Figures 5 and 8) reveals a different lower crustal structure under the coastal region in each section. Figure 8 shows an intrusion of lower crustal material into the upper crust at a vertical exaggeration of 10:1, but even at a 1:1 vertical exaggeration as shown in Figure 15 the difference between the two cross sections is distinct. As discussed previously in Section III, a combination of the observed gravity anomalies and offshore geology require this
structure. The relatively shallow basement shown near km 400 in Figure 8 requires a steep dip for the Moho through that region to fit the observed gravity field. This dip, in turn, requires the intrusion of the lower crustal block into the upper crust under the coastal gravity high.

Two alternative structures could also be constructed to fit the gravity profile. The less severe modification would be to change the dip of the Moho under the lower crustal block, and allow the higher density mantle material to be higher in the region under the coast. This would reduce the size required of the lower crustal block to obtain the gravity anomaly observed on the coast. A more severe modification to the structure illustrated in Figure 8 would be to place the basement material deeper under the edge of the continental shelf. This would allow the Moho between the trench and the coast to dip less steeply, hence raising the mantle material higher under the coast, and allowing the lower crustal block to be smaller. For a maximum reduction in the size of that block, a combination of these alternative structures would be required.

A less severe version of the second alternative might be considered because the shallow basement indicated on Figure 8 for the region under the shelf edge was put in the model because the data profiles were taken from a trackline passing directly over the +20 mg1 high seen northwest of Pisco. This anomaly northwest of Pisco is the
most pronounced expression of the gravity high which extends north-westward along the shelf edge from the Paracas Peninsula. However, the seismic reflection profiles along this trackline did not detect as shallow a basement under the shelf edge here as they did on all the crossings to the south. Hence it may be possible that while the gravitational expression for the extension of the coastal structure offshore toward northwest along the shelf edge is highest at the Pisco profile trackline, the northwestward dip of the basement may begin south of the Pisco profile. Because the northwest portion of the Pisco Basin extends into this region it is likely that the basement under the shelf edge deepens to the northwest. Because the gravity computations for the model assume two-dimensionality, i.e., the features extend to infinity in both directions from the plane of the cross section, an alternative model section would place the 2.75 g/cm³ basement layer under the shelf edge at km 400 deeper below the surface than shown in Figure 8.

However, any combination of the alternative structures discussed above that would completely eliminate the lower crustal block under the coast would require shoaling of the Moho between km 400 and km 500, and would simply lead to another anomalous structure. This structure would have a very steep dip for the Moho landward of km 500 under the flank of the Andes in order to reach the depth of 60 km below sea level suggested by the gravity data over the
Andes, and indicated by James (1971a) for this region.

Results of the gravity models presented here as well as those published by Ocola and Meyer (1973) indicate a deep crustal structure under the Andean altiplano that is similar to that indicated by James (1971a), but show a thicker crust under the eastern flank of the Andes. James estimated a crustal thickness in this region of about 50 km to satisfy the Rayleigh wave phase velocity dispersion curve. Ocola et al., (1971) suggest that James' model is an underestimate of the crustal thickness, and that the inversion of Rayleigh wave data is insensitive to compressional wave velocities, so James' model is relatively insensitive to the depth of the Moho. Ocola et al., (1971) had the advantage of a reversed seismic refraction line on the altiplano. Ocola and Meyer (1973) show that the thick crust indicated by both refraction and gravity models is in agreement with the delays observed on the altiplano compared with observations on the coast in arrival times for PKP compressional waves traveling vertically through the crust.

Another clear requirement of the gravity anomalies is for the crust to remain relatively thin between the trench and the west flank of the Andes, and then to thicken rapidly toward the east. Previous, less detailed gravity models by Hayes (1966) and Ocola and Meyer (1973) also indicate this structure, and it can be inferred from the earthquake seismology studies of Stauder (1975). The Mollendo cross
section shown at 1:1 vertical exaggeration in Figure 10 best illustrates this structure, but the reasons for it are seen in Figure 5. The change in the dip of the Moho from about 6° to about 26° that occurs under the western flank of the Andes at km 933 on the section is well controlled by both gravity and seismic refraction. The very steep gradient in the gravity anomaly profile between the trench and the Andes (Figure 5) suggests the Moho does not dip steeply through this region, but the seismic refraction at km 980 indicates the Moho to be about 50 km below sea level at that point. Changing the density of the relatively small sedimentary blocks on the continental margin does not affect the dip of the Moho appreciably.

The densities indicated on the crustal and subcrustal cross sections are obtained primarily from the seismic refraction velocities observed for the regions indicated in Figures 5, 7, and 8 by using the empirical relation between density and compressional wave velocity reported by Nafe and Drake (1961) and Ludwig et al. (1970). However, the densities for the upper crustal blocks on the continental margin and the density of the 2.75 g/cm³ used for the surface structure in the coastal region on the Pisco and Mollendo cross sections are based primarily on densities applicable to the rock types indicated by geologic studies. Coastal geology (Steinmann, 1930; Jenks, 1948; Anonymous, 1969; and Masias, 1975) indicates Pre-Cambrian, Paleozoic, and Mesozoic rocks which include gneisses, granodiorites, andesites and basalts,
and some relatively thin sediments. The average density of these rock types is estimated to be $2.75 \text{ g/cm}^3$ (Woollard, 1962; and Clark, 1966). Densities for the offshore margin blocks are estimated assuming compacted, dewatered sediments of continental and oceanic origin, and are in approximate agreement with that indicated by others (Fisher and Raitt, 1962; Hayes, 1966; and Ludwig et al., 1970).

Measuring the area included on the cross section by the 2.0 and 2.5 g/cm$^3$ blocks on the margin, and comparing that with areal extent of the cross section of the sediment layer overlying the Nazca Plate, calculations show that at least 50% of the sediment on the plate has been subducted during the history of the Peru-Chile Trench. Furthermore, any terrigenous sediments in these margin blocks would require a corresponding increase in the amount subducted. This calculation assumes a constant sediment thickness on the Nazca plate and subduction that started approximately 180 million years ago, as suggested by land geologic evidence for the beginning of orogenic activity in the Andean region (Jenks, 1948; Cobbing and Pitcher, 1971; and Steward et al., 1974). Orogeny in the Andean region probably more accurately reflects the beginning of subduction along the Peru-Chile Trench than dates for the opening of spreading centers in the Atlantic or Pacific Oceans and a causal relationship is postulated to exist between the orogeny and subduction processes because the trench and the Andes parallel each other for thousands of km, and seismic
activity extends from the trench under the Andes. It is not possible
to establish a causal relationship between any one spreading center
and a subduction zone because crust generated at a spreading center
can result in subduction at many different places on the earth's
surface.

The most surprising finding of the gravity survey is the 200 km
northwest offset in the gravity anomaly associated with the Peru-
Chile Trench compared with the bathymetry of the trench (see Section
II). A mass column in the trench axis at the end of the Nazca Ridge
(15° 15' S. Lat.) has 600 m less water, or 600 m more rock, than a
mass column 200 km northwest, at 13° 45' S. Lat. in the trench axis.
However, the gravity anomaly is 53 mgl more positive at 13° 45' S.
Lat. where the negative anomaly associated with the trench is at a
minimum (see Figure 2). This requires the rock under a mass column
off the northeast end of the Nazca Ridge to be less dense than rock
in a mass column under the axis of the trench for at least 200 km
northwest along the trench, and is consistent with subduction of the
Nazca Ridge. The crustal and subcrustal cross section of the Nazca
Ridge (Figure 7) shows substantially lower density material down to
18 km below sea level, compared to either side of the ridge.

However, this qualitative explanation of how the gravity anomaly
could be more negative off the end of the Nazca Ridge where there is
600 m more rock than 200 km to the northwest does not explain why
the gravity field along the trench has its relative maximum at 13° 45' S. Lat. It does seem more than mere coincidence that the general discontinuity seen in the gravity anomaly patterns occurs at about 13° S. Lat. (see Section II) and that the Abancay Deflection (Masias, 1975), north of which the coastal mountains appear offset about 100 km landward, also intersects the coast at about 13° 30' S. Lat. (see Section I). The motion of the Nazca Plate relative to the South American Plate is at a direction of about N 81° E and a convergent rate of 10.3 cm/yr (Minister et al., 1974) and the Nazca Ridge trends N 45° E approximately normal to the trench axis. Assuming the Nazca Ridge is linear and continuous and extrapolating these rates and strikes back in time shows that 3.3 million years ago the intersection of the Nazca Ridge and the Peru-Chile Trench was 200 km northwest of its present location. Since then 275 km of the ridge would have been subducted, hence if the Nazca Ridge was never more than 275 km longer than it is now it would never have been subducted north of 13° 45' S. Lat. From 13° 45' S. Lat. the extended axis of the Nazca Ridge would intersect the coast near 13° S. Lat. The inverse argument is that any features observed near 13° S. Lat. which are older than 3.3 million years are probably not related to the subduction of the Nazca Ridge because that subduction would occur north of approximately 13° S. Lat. prior to 3.3 million years ago. Isostatic compensation of the Nazca Ridge is convincingly
demonstrated by comparing the free-air gravity anomaly map and the bathymetry map (Figures 2 and 3). It is also obvious in the crustal and subcrustal cross section of the Nazca Ridge shown in Figure 7. The free-air anomaly over the ridge averages less than +20 mgl. If it were uncompensated the average would be +75 to +100 mgl. Hayes (1966) suggested that the Nazca Ridge was compensated, and Fisher (1958) working with seismic refraction data from Expedition Downwind estimated a crustal thickness within 10% of that shown in Figure 7.

The continental margin opposite the end of the Nazca Ridge is much narrower than it is either to the north or south. Erosion of the margin by the higher topography of the ridge as it is subducted could explain the relatively steep, narrow slope. However, this hypothesis is not consistent with the observation of pelagic sediments from the Nazca Ridge, high in calcium carbonate content, found accreted on the margin opposite the ridge (Kulm et al., 1974) and also on the margin 1800 m above the trench floor 100 km to the north (Rosato, 1974). This displacement to the north may confirm that the position of interaction of the ridge with the trench is moving to the south, as discussed above.

The two shallow cross sections over the Pisco and Mollendo Basins (Figures 11 and 13) indicate 2.2 km and 1.4 km respectively as the probable sediment thickness in the basins. The procedure used in constructing these models requires a complete crustal and
subcrustal cross section nearby. From the complete section it is possible to determine the gravitational effect of the lower crustal and upper mantle structures. The same effect is then generated for the shallow sections by a single underlying layer that has no structural significance other than to produce a gravitational field equivalent to that determined by the lower crustal and upper mantle mass distributions in the complete section. The sediment thicknesses determined for these basins show good agreement with estimates of thickness by Johnson et al., (1975) using wide angle seismic reflection and refraction.

Masias (1975) identifies the Lima Basin as extending along the upper continental slope from 10° to 14° S. Lat. Free-air gravity anomalies associated with the Lima Basin include the -70 mg/l low near 78° W. Lon. on the north end of the map (Figure 2), and -90 mg/l low near 13° S. Lat., 77° W. Lon., and the -40 mg/l low near 14° S. Lat., 76° 45' W. Lon.

The Mollendo Basin is identified as extending along the upper slope from 16° S. Lat. (Masias, 1975) south to at least 20° S. Lat. and perhaps to 23° 30' S. Lat. (Coulbourn and Moberly, 1975). The large negative anomaly at 17° S. Lat. is the most pronounced gravitational expression of this basin, but the -50 mg/l gravity low on the south end of the map and the contorted contours near the coast at 16° S. Lat. may be caused by an extended Mollendo Basin. Masias
(1975) uses the name Arequipa rather than Mollendo when describing this basin.

Hayes (1966 and 1974) noted the "Bolivar Geosyncline or its counterpart to the south" as extending from 10° to 16° 30' S. Lat. based on his gravity anomaly map. This feature is apparently analogous to the Lima Basin which Masias identifies from seismic reflection profiles. The -70 mgl gravity low on the north end of the gravity map (Figure 2) suggests that a detailed gravity map extending north to 10° S. Lat. could confirm the presence of the Lima Basin in that region. While Figure 2 shows no evidence for a slope basin between 14° and 16° S. Lat. (opposite the end of the Nazca Ridge) as suggested by Hayes (1966), it does seem probable that a slope basin exists between 10° and 20° S. Lat. except where the continental slope is pinched by the Nazca Ridge. This could imply a general feature along the Peru-Chile Trench similar to the upper slope break and basin seen on many trench crossings in the Western Pacific (Karig and Sharman, 1975).

Coulbourn and Moberly (1975) suggest that such a feature exists off Chile and that it may indicate accretion of Nazca Plate sediments onto the margin and uplift under the upper slope break possibly as a horst, warping the continental sediments upward and causing landward migration of the basin. Masias (1975) also suggests landward migration of upper slope basins by the same process but notes that
the migration direction may be seaward if there is more rapid uplift under the edge of the continental shelf.

While the gravity anomalies do not distinguish between terrigenous and pelagic sediments and even the most detailed seismic evidence leaves the tectonic history of the margin in doubt (Prince and Kulm, 1975; Hussong et al., 1975; and Masias, 1975), the isostatic disequilibrium indicates ongoing tectonic processes. The enormous free-air gravity anomalies, negative over the trench and positive over the Andes, show that a component of the tectonic force is down under the trench and up under the Andes. On a finer scale, the gravity anomalies over the Pisco section, the Pisco Basin section, and the Mollendo Basin section indicate regions of mass excess under the relative gravity highs which suggests uplift and mass deficiencies under relative gravity lows associated with sediment ponding in structural depressions and perhaps accretion on the continental slope.
V. CONCLUSIONS

The above analysis of free-air gravity anomalies mapped on the margin of southern Peru together with evidence from bathymetry, seismic reflection and refraction, seismicity, and land and marine geologic studies indicate the following:

The Nazca Ridge is isostatically compensated by a relatively thick crust whose layers have slightly lower density than similar layers of oceanic crust on either side of the ridge. Most of the increase in thickness occurs in the lower crust. A light mass column and narrow continental margin observed at the intersection of the Nazca Ridge and the Peru-Chile Trench are consistent with subduction of the ridge.

Structural models constrained by free-air gravity anomalies show that the crustal thinning seaward of the trench is not as pronounced as Hayes (1966) reported. The crust, including the water layer, thins from 10.5 km to 8.5 km over a horizontal distance of 380 km on the Mollendo Section, and not at all on the Pisco section. Landward of the trench the crust thickens gradually to 25 to 30 km under the southwestern flank of the Andes. From there the crust thickens rapidly toward the northeast to about 70 km thick under the central Andes, or altiplano. The Pisco section suggests a rupture of the crust at depth under the coast, and the Benioff zone under the
altiplano may be nearly horizontal. Since the Mollendo section shows neither of these effects, the subduction process is concluded to be different on each side of the Nazca Ridge.

Uplift of crustal rocks of the upper slope and outer continental shelf has occurred. Sedimentary structures landward from the edge of the continental shelf are terrigenous while seaward they consist of both turbidites and accreted pelagic sediments. Lower crustal and upper mantle mass distributions enhance the relative gravity lows produced by the basins formed on the upper slope and shelf. Sediment thicknesses computed from the observed gravity anomalies are estimated to be 2.2 km in the Pisco Basin and 1.4 km in the Mollendo Basin.

The coastal structure seen extending from 17° S. Lat. north to the Paracas Peninsula can be traced to the northwest along the edge of the continental shelf to about 13° S. Lat. If the structure continues north of 13° S. Lat. it is offset at least 50 km to the northeast. The continental shelf is over 30 km wide from the Paracas Peninsula to 10° S. Lat. It narrows to less than 20 km wide between Paracas and 15° S. Lat., and narrows still more toward the south to about 10 km wide at 16° S. Lat.
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