Title: DEFORMATION IN THE PERU TRENCH, 6°-10°S

Abstract approved: Redacted for privacy

L. D. Kulm

Detailed surveys of several segments of the Peru Trench show that the region between 6° to 10° S is an area of recent deformation. Seismic reflection records across the axis of the trench show faulting, uplift, and tilting of the sedimentary fill and the acoustic basement. Uplift of the acoustic basement beneath the trench is greatest at 7°40'S and 9°20'S where ridges are elevated above the trench floor. Turbidites occur on top of the ridge at 9°20'S and seaward of the ridge in a basin which is elevated 300 m above the main trench floor. Based upon a hemipelagic sedimentation rate of 1.7 cm/1000 yr, the age of uplift of the ridge is dated at less than 10,000 yrs. B. P. Similarly, the age of uplift of the elevated basin seaward of the ridge is dated at less than 34,000 yrs. B. P. near the ridge and at less than 53,000 yrs. B. P. at the seaward edge of the basin.

The trench shoals and turns eastward as one proceeds from south to north along the axis. It divides naturally into three segments...
separated by the axial ridges at 7°40'S and 9°20'S. The southern segment trends N31W and has an axial depth of 6300 m; the middle segment trends N24W at 6200 m; and the northern segment trends N11W at 5800 m.

The upper continental slope is characterized by submarine canyons which funnel sediments into the trench axis. The lower slope is characterized by benches. These benches may define old imbricate thrust sheets. Ridges in the axis are thought to be new imbricate thrust sheets which are forming at the boundaries between segments of the subducted lithosphere.

An apparent fracture zone trending N45E enters the area from the southwest. Two turbidite basins (B1 and B2) trending N9E occur northeast of this fracture zone. Turbidite deposition ended in these basins 5100 yrs. ago. The basins intersect the trench axis just north of the ridge at 7°40'S and are presently 700 m above the trench axis. This relative difference in depth is attributed to a combination of subsidence of the trench and uplift of the oceanic plate upon initiation of thrust faulting which presumably occurred 5100 yrs. B.P. There is still insufficient data to determine the exact origin of these basins.

From the regional structure, it appears that the lower continental slope of South America is underthrusting the upper continental slope along old imbricate thrust faults beneath the Peruvian continental slope. This overthrusting has caused uplift and accretion of the
continental slope and shelf edge and subsidence and sediment infilling of the area between the shelf edge and the coastline.

The author suggests that the seismic gap (present lack of large magnitude shallow earthquakes in this area) may be in part due to the highly fractured and deformed nature of the subducted Nazca Plate. Finally, using variable motion along old imbricate thrust faults, the imbricate thrust model provides mechanisms for reorientation of the trench and for episodic subduction of the oceanic plate beneath the trench axis.
Deformation in the Peru Trench, 
6°-10°S

by

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DEFORMATION IN THE PERU TRENCH, 6°-10°S

INTRODUCTION

The world, which took but six days to make, is like to take six thousand to make out.

Sir Thomas Browne

On May 31, 1970 the earth spontaneously ruptured and killed an estimated 70,000 people in the worst natural disaster in the history of the western and southern hemispheres (Cluff, 1971). The earthquake occurred beneath the continental shelf off northern Peru at 9.2°S, 78.8°W and at a focal depth of 43 km; the loss of life occurred mainly in and around the city of Huaras, Peru. To predict these destructive earthquakes, man must understand their cause. Plate tectonic theory explains the cause of the 1970 earthquake as the release of stress brought about by the crust of the Pacific Ocean underthrusting the South American continent (Isacks and Molnar, 1971, and others). The majority of the world's destructive earthquakes are associated with postulated zones of convergence between lithospheric plates like the one along the western coast of South America.

Figure 1 shows the Peru-Chile Trench, the convergent boundary where the Nazca oceanic plate is underthrusting the South American continent. The area of this study lies between 6°S and 10°S
Figure 1. Location map showing area of study (hatchured box). Boundaries of Nazca Plate (heavy dashed line); trend of Peru-Chile Trench and Andes Mountains; areas of east-west lineations; and magnetic sea floor spreading anomalies are after Herron (1972).
latitude and 79°W - 82°W longitude. The region investigated includes the leading edge of the oceanic plate, the trench, and the continental slope.

Spreading rates on the East Pacific Rise are among the highest in the world. Rea et al. (1973) have reported half-spreading rates of 8.2 and 8.3 cm/yr for 6°S and 11°S latitude, respectively. The convergence rate along the Peru-Chile Trench is calculated at 10 cm/yr (Minster et al., 1974). The distance between the divergent and convergent boundaries is less at these northern latitudes than elsewhere on the Nazca Plate. On the South American continent between these latitudes the Andes Mountains parallel the coastline and change trend from northwest in Peru to northeast in Ecuador. This change in trend occurs at the bulge in South America at approximately 6°S latitude and is known as the Huancabamba deflection (Fig. 1). In this paper the author attempts to determine the structure and tectonics of the leading edge of the Nazca Plate and Peru Trench and to relate these to:

(1) the high convergence rate of the oceanic and continental plates;
(2) the absence of large magnitude shallow earthquakes in this area;
and (3) the change in trend of the continental structures adjacent to this area.

Previous studies do not contain sufficient data to determine the structure of the Nazca Plate and Peru Trench in this area. Herron (1972) mapped the magnetic anomalies for the Nazca Plate but her
data are incomplete in the northeastern corner of the plate. Hayes (1966) published one oblique geophysical crossing of the Peru Trench at 6°S and a free air gravity anomaly map of the entire Peru-Chile Trench. Menzies et al. (1973) published a bathymetric profile. Kulm et al. (1973b) discussed the occurrence of a basalt ridge in the trench axis. With the exception of these investigations there is essentially no work published on the segment of the Peru-Chile Trench pertinent to this study.

Oregon State University (OSU) and Hawaii Institute of Geophysics (HIG) are conducting a detailed investigation of the upper part of the subduction zone as part of the International Decade of Ocean Exploration (IDOE) Nazca Plate Project. The bulk of the data used in this study was collected by the R/V YAQUINA of OSU and by the R/V KANA KEOKI of HIG on cruises in 1972 and by the R/V KANA KEOKI in 1973. Earth orbiting satellites were used for navigation. Bathymetry and shallow seismic reflection data were taken with a 3.5 kHz source and standard recording instruments. On the YAQUINA seismic reflection records were made using twin 40 cu. inch air guns and standard single channel hydrophone streamers, amplifiers, and recorders. Band pass filter settings were generally 30-160 Hz. The data were recorded on an EPC graphic recorder with a 4 second sweep rate. The KANA KEOKI used a 300 cu. inch air gun as an acoustic source (A 1000 joule sparker augmented by a 20 cu.
inch air gun was used on the continental slope on several occasions), standard single channel recording equipment with band pass filters set at 40-100 Hz, and a 5 second sweep rate. Sediment data were obtained from piston cores and free-fall cores and from the World Ocean Sediment Data tape made available by Scripps Institute of Oceanography (SIO). Bathymetric data compiled from other cruises was kindly made available by T. E. Chase of SIO.

REGIONAL GEOLOGY, STRUCTURE, AND SEISMICITY

The earth was made so various, that the mind
Of desultory man, studious of change
And pleased with novelty, might be indulged.

Cowper

According to plate tectonic theory, the geology of the Andes Mountains reflects the history of the convergence of the oceanic and continental plates and the associated subduction process (James, 1971b, and others). Figure 2 shows the volcanic sediments, intrusive bodies, and major faults associated with the Peruvian segment of the Andean ranges. Based upon the orientation of the igneous rock bodies and the structural trends, the Andes change trend three times in the region. According to Jenks (1956), south of 18°S the trend is S10W; from 18°S to 14°S the trend is N55W; from 14° to 8°S the trend is N30W; and north of 5°S it is N15E. The region between 5°-8°S is
Figure 2. Geologic map showing major igneous rock bodies and major faults. Small rectangle at 5°00'S delineates area of Fig. 3. Seismic gaps are areas in which no shallow high magnitude earthquakes have occurred within the last thirty years (after Kelleher, 1973). Sources for the geology and fault patterns are: geologic map of Peru (1969), geologic map of Ecuador (1969), tectonic map of Peru (1970), and geologic map of South America (1964).
one of two areas along the western margin of South America where east-west lineations occur (Jenks, 1956).

Between 2°N and 20°S Kelleher et al. (1973) identified three areas along the South American-Nazca Plate boundary where no shallow focus earthquakes greater than magnitude 7.7 have occurred within the past 30 years. These seismic gaps are indicated in Figure 2. Although the entire Peru-Chile Trench is seismically active (Barazangi and Dorman, 1969), the seismicity apparently has a regional segmental character (Kelleher et al, 1973). Large magnitude earthquakes, which account for most of the world's total seismic energy release, are not evenly distributed along the Peru-Chile Trench. Two possible explanations are suggested for this phenomenon: 1) there are a large number of small magnitude (<3.0) earthquakes occurring which cannot be detected because of the lack of a closely spaced seismograph network in this area and which account for the difference in total seismic energy release observed, and 2) these seismic gaps are areas where only a small amount of the total seismic energy is being released at present. If the second case is true, a tectonic explanation is necessary. Kelleher's seismic gaps show an excellent correlation with the inflection points in the Andean structural trends (Fig. 2). There may be a relation between the change in structural trends and the change in the character of the seismicity which might be reflected in the type of subduction that is
occurring along this particular segment of the convergent boundary.

Between 4° and 8°S the Andes are distinctly different from the Andes to the north and south because of the occurrence of east-west lineations. According to Jenks (1956), these east-west structures occur west of the Rio Maranon (approximately 78°W longitude) between about 6°30' and 7°45'S. Geologic quadrangle maps are available only for the area south of 7°30' (Fig. 3). The east-west lineations are clearly seen in Figure 3 and in a more general way in Figure 2. Several east-west faults occur along the coast of northern Peru (Fig. 2). Ham and Herrerra (1963) place the center of this anomalous area, the Huancabamba deflection, at 6°S. If the Andean trends (N15E and N30W) are extended into this anomalous area until they meet, the intersection occurs at about 6°S (Fig. 1).

This region is also anomalous because of the small volume of igneous material (Fig. 2). The Huancabamba deflection has been an area of minor igneous activity at least since the beginning of the Mesozoic, being essentially inactive since early Tertiary time. Intrusive rocks make up 60% of the surface in the area between 8° and 9°S, but less than 20% between 7°30' and 8°S (Cossio and Jaen, 1967). Most of the volcanic material is associated with upper Cretaceous-lower Tertiary or upper Triassic and Jurassic strata. There are only two small areas of Pliocene-Quaternary volcanic sediments. With the exception of an area of Jurassic-Cretaceous intrusive rocks
Figure 3. East-west lineations in the area of the Huancabamba Deflection. See Fig. 2 for location. After Cossio and Jaen (1967).
on the westernmost coast of Peru, the intrusive rocks belong to the group loosely dated as late Cretaceous to early Tertiary. In contrast, the areas north and south of the anomalous zone are characterized by recent vulcanism, major seismicity and major tectonic activity throughout most of geologic time, perhaps since the Precambrian (Fig. 2).

The continental crustal structure in the vicinity of the Huancabamba deflection is essentially unknown. Case et al. (1971) report a maximum thickness of 30-35 km beneath the Cordillera Central of western Colombia at 6°N. Farther south (1°N) in Colombia, Case et al. (1973) report a slightly greater thickness of 45 km. They suggest that the crust may be thickening toward the south. In central Peru, James (1971a) reports a maximum crustal thickness of 70 km beneath the western Cordillera and western Altiplano region. Ocola and Meyer (1973), however, propose that the crust beneath southern Peru and northern Chile has a maximum thickness greater than 70 km. Whether the crust thins between 12°S and 4°S or remains constant does not give any direct evidence for the crustal thickness beneath the Andes in the vicinity of the Huancabamba deflection. Crustal thicknesses beneath the continental shelf (7°-8°S) are 30-40 km according to seismic refraction work done by HIG-OSU in 1972 (S. H. Johnson, personal communication). It is possible then that the crust in the area of the Huancabamba deflection is transitional in
thickness and therefore has a thickness intermediate between 55 and 70 km.

In summary, the Huancabamba deflection is a broad band covering some 550 km in a north-south direction. In this area there are east-west structural lineations and a paucity of plutonic and volcanic activity at least since the Paleozoic. The area separates a tectonically active area of large magnitude seismicity and recent vulcanism to the north from a similarly tectonically active region of different structural trend to the south.

**BATHYMETRY AND MORPHOLOGY**

Under every deep a lower deep opens

Emerson

The first task of this study was to produce a new and more detailed bathymetric map of the region (Fig. 4) and to identify the major morphologic features in the area. The bathymetric map will be used in the structural and tectonic interpretations of the area which follow in later sections.

A 100 m contour interval was chosen for the bathymetric map because most of the depths at trackline intersections differ by less than 100 m and because from one trackline to another there are correlatable features which have a relief of less than 200 m but more
Figure 4.  Bathymetric map for area from 6°05'S to 10°00'S and 79°00'W to 82°00'W. Depths corrected for sound velocity in water. Prepared October, 1973 (located in pocket at back).
than 100 m. The original bathymetric records were digitized in uncorrected fathoms and then converted to meters corrected for sound velocity in water using the Matthews Tables for zone 42. All available bathymetric data was used on the continental shelf and slope. Because the older bathymetric data from other sources was of a variable and unknown quality, it was discarded in favor of the OSU and HIG data, which was controlled by satellite navigation. For the trench and oceanic plate, the older bathymetric data were in such poor agreement with the newer OSU-HIG data that they were discarded altogether with the exception of one Scripps Institution of Oceanography track. To help eliminate subjectiveness and bias in the contouring on the oceanic plate, the data were first contoured using a computer contouring program at Hawaii Institute of Geophysics. The resulting data were recontoured by hand. The tracklines used in making the bathymetric map are shown in Figure 5.

The maximum depth of the trench axis on each crossing is plotted as a function of latitude to show the change in water depth from north to south (Fig. 6). The depths of those basins seaward of the trench axis (B1, B2, B3), which contain turbidites (see section on sediments), are also shown in Figure 6.

Profiles 1-23 (Fig. 7) are depth rather than time plots both for the surface and subsurface. The vertical exaggeration is 13:1 for all the profiles. The sediment thickness, faults, and schematic reflectors
Figure 5. Tracklines for bathymetry used in compiling Fig. 4. Does not include data obtained from SIO. Heavy lines are tracklines shown as profiles (Fig. 7) and as seismic reflection records (Figs. 13-22).
Figure 6. Maximum depth of main trench axis and turbidite basins versus latitude. Inset shows location and trend of features.
Figure 7. Schematic seismic reflection profiles across the Peru Trench (1-21) and across apparent fracture zone (22-23). See Figure 5 for location. East is always on the right. Dotted line is prominent secondary oceanic sediment reflector. All sediment reflectors and all faults are schematic. Depths are corrected for sound velocity in water. Average velocity of 1.7 km/sec is assumed for all sediments.
shown in Figure 7 are discussed in later sections.

**Continental Shelf and Slope**

The continental shelf break in this region occurs between 100 and 200 m (Fig. 4). Gradients on the upper continental slope average 1:45 to 1:35. The upper slope is dominated by numerous submarine canyons. The deepest and most striking canyons occur in the northern area where the shelf is narrowest. A prominent canyon system is present in the region around 6°45′ S, 80°55′ W and has a relief greater than 1500 m (Fig. 4).

The topography of the lower continental slope is dominated by numerous benches. Gradients between these benches are generally around 1:8 to 1:7 but may be 1:2 or greater at the continental slope-trench axis interface. The benches are flat or dip toward the continental slope on most profiles, but the apparent dip of the benches is down the continental slope in a few cases. Their width varies from 10 km (profile 10, 2600 m) to 0.15 km (profile 5, 4600 m) or less. The benches appear to merge laterally into the slope, rather than end abruptly. Some of these features can be traced continuously for distances up to 70 km (profile 11-16, 4000-4400 m). Most of the benches plunge north or south along the slope. The degree of plunge ranges from 1:1000 (profiles 21 and 22, 5200 m) to 1:25 (profiles 1-3, 3800-3100 m). Most profiles show at least two benches on the
continental slope. To the north (6°-7°S) all benches plunge to the north; between 7° and 9°S some plunge north and some plunge south, and between 9° and 10°S all of the benches plunge to the south. In general, benches between 6° and 7°S (2800, 3100, 3900, 4100, and 4600 m) occur at shallower depths than those between 9° and 10°S (4100, 4700, 5000, and 5200 m). Unfortunately, these complicated features were not surveyed in enough detail to receive the attention they deserve.

**Trench Axis**

The most striking aspect of the trench axis is the regional change in depth of the trench floor from 5800 m to 6200-6300 m over a distance of less than 50 km (Figs. 4 and 6). Superimposed upon this sudden change in depth is a gradual shoaling to the north. The trench axis can be divided into a northern and southern province. In the northern province, the axis is 8-14 km wide and appears to widen slightly to the south. The northernmost crossings (profiles 2 and 4, Fig. 6) show an almost flat floor while to the south the floor dips landward (profiles 5, 6, and 7).

The trench floor in the southern province is narrower, being 2-5 km wide. It broadens to 11 km around 8°15'S and to 12 km at 9°25'S. With two exceptions, the floor appears flat with a very slight depression in it. On profile 10 there is a marked narrow depression
in the center of the axis and on profile 11 the axis appears bowed up very slightly. In general, the trench floor is flatter and has less relief than in the northern province.

Ridges

Three prominent ridges (R1, R2, R3; Figs 4 and 7) are recognized in the area investigated. The first ridge (R1, profiles 6-9) has an almost constant depth and shape with the exception of profile 8 where the ridge is lower. It apparently plunges north of profile 6 and the low feature immediately to the west of the trench floor (profile 5) may be the same ridge. South of profile 9, the ridge apparently rises in elevation (profile 10) and merges into the ocean floor.

The second ridge (R2, profiles 8, 9, 10) plunges northeast and narrows on successive crossings. Its depth increases from 4400 m (profile 10) to 5400 m (profile 8) and on the basis of other data discussed later, appears to merge with the trench north of profile 8. A saddle occurs between profiles 8 and 9 at 5200 m (Fig. 4). To the south of profile 10 the ridge broadens and is indistinguishable from the rest of the oceanic plate.

The third ridge (R3) occurs between 8°45' and 9°25'S and occupies the axis of the trench (profiles 11 - 19; Kulm et al., 1973a). At 9°10'S (profiles 13-14) the ridge changes from a single to a double peaked feature. To the north it appears to be discontinuous and is lower
in relief (Fig. 4; profiles 11-13). In the area of the double peak, the depths are around 5800 m on profiles 11 and 13 but 5500 m and 6000 m on profile 12. The ridge ends somewhere to the north between profiles 10 and 11. At its southern end the ridge plunges and terminates between profiles 19 and 20. Where the ridge appears as a single peak it is about 5400 m deep with the exception of one prominent peak at 5000 m (Fig. 4).

Basins

Seaward of the main trench axis there are three prominent long and narrow basins (B1, B2, B3; Figs. 6 and 7). West of the ridge R1, there is a basin (B1, profiles 7-10). It has a nearly constant depth (Fig. 6) and appears to merge with the ocean floor north of profile 7. To the south it widens gradually to 1.9 km. The basin narrows somewhat south of profile 9 to 1.4 km. Between ridges R1 and R2 there is another basin (B2; profiles 8 and 9). This basin and ridge R2 plunge northeast and merge with the main trench axis (Figs. 4 and 6). South of profile 9 the basin may simply terminate between the two ridges (R1 and R2) or it may rise (profile 10) and merge with the ocean floor.

At 9°S the third ridge (R3) divides the trench into two basins, an inner deeper basin (the main axis) and an outer shallower basin (B3; profiles 11-19). This basin like the ones to the north is elevated
above the trench axis on the seaward side of the trench. It has a width ranging up to 4 km and a depth of 6000-6200 m in the region adjacent to the single ridge (Figs 4 and 6; profiles 14-19). Where the ridge bifurcates the basin is 2.5 - 4 km wide and shoals to depths ranging between 5900 m and 6100 m (profiles 11-13). This outer basin is generally 150-250 m shallower than the trench axis and apparently deepens to merge with the main trench axis south of ridge R3 (Fig. 4).

**Fracture Zone**

A probable fracture zone, trending N45E, enters the area from the southwest (Figs. 4 and 8; profiles 22 and 23). Mammericx et al. (1974) show a topographic low on the Nazca Plate with this same trend and position. This probable fracture zone has the same trend as a probable fracture zone found between 5°15' and 6°00'S (L. W. Kroenke, personal communication). On profile 23 the maximum depth of the fracture zone is 4950 m with a maximum height on the western side of 4100 m and on the eastern side of 3950 m. The width is about 75 km. There is no discernible regional difference in depth along this profile. On profile 22 the maximum depth of the fracture zone is 5300 m with a maximum height on the eastern side of 4100 m and on the western side of 4400 m. The width is about 40 km. The regional depth appears to be about 300 m shallower to the west. None of the other profiles show any topographic expression indicative of a fracture.
Figure 8. Shows all tracklines in area of apparent fracture zone. Location and trend of apparent fracture zone and basin B1 are shown.
zone except profile 10 which crosses the two basins (B1 and B2; Fig. 8). These two basins do not lie along the same trend (N45E) as the apparent fracture zone but rather they trend N9E. If these two basins are the northeastern extension of the fracture zone, then the apparent offset (Fig. 4) and the change in trend can only be accomplished by deep fracturing and rotation of the oceanic plate or by a change in spreading direction when the ocean floor was formed. This idea will be explored further.

Regional Difference in Water Depth of the Ocean Floor

The profiles in Figure 7 have been separated into three geographic groups (Fig. 9). Deep ocean basin depths in the northern group (Fig. 9a) are 200 m to 300 m shallower than the southern groups. The intermediate group (Fig. 9b) has an average depth curve similar to that of the southern two crossings (Fig. 9c) except for the presence of the high ridge at the trench-plate interface. This regional deep ocean depth difference (Fig. 9d) appears on a new map of the southeast Pacific (Mammerickx et al., 1974) and has the same magnitude as the regional depth difference across the apparent fracture zone in profile 22 (Fig. 7).
Figure 9.  
A. Bathymetric profiles 1-10, northern province of trench.

B. Bathymetric profiles 11-19, intermediate province.

C. Bathymetric profiles 20 and 21, southern province, similar to B except that high ridge at oceanic floor-trench axis interface is absent.

D. Envelope of curves in A, B, C superimposed showing that ocean floor depths in A are 200-300 meters shallower than in B and C. Dotted line is crossings of basins B1 and B2 which lie below the regional depth of the ocean floor.
SEDIMENTS

By the agitation of the winds, the tides and currents, every moveable thing is carried farther and farther along the shelving bottom of the sea, towards the unfathomable regions of the ocean.

James Hutton

Sediment Thickness

Sediment thickness is highly variable on this portion of the Nazca Plate. The thickness as measured from seismic reflection records ranges from 0-0.3 seconds. For the purpose of converting the time sections (seismic reflection records) to depth sections (Fig. 7) a constant velocity of 1.7 km/sec was assumed for all sediments. This first approximation of the velocity structure agrees well with the velocities found by seismic refraction modeling (Goebel, 1974) for the sediments on the Nazca Plate and in the trench axis immediately to the south of this area. A velocity of 1.7 km/sec gives a maximum thickness of 500 m for the Nazca Plate sediments in the area studied. The high local variability in sediment thickness and the limited amount of good seismic reflection data preclude the construction of a meaningful isopach map. The local variation in sediment thickness is superimposed on a regional difference in sediment thickness. Nazca Plate deposits are thicker in the north (range 0.15-0.25 sec., profiles 2-7) than sediment thicknesses in the south (range
0.08-0.17 sec., profiles 11-14, 20-21). The greater thicknesses to the north are attributed to two factors: 1) biological productivity increases to the north as one approaches the equator, and 2) the Humboldt Current, which is part of the upwelling system along the west coast of South America, swings west toward the Galapagos Islands at 6°S.

A prominent secondary reflector is visible on many of the seismic reflection records (Figs. 14 and 22). It appears most commonly to the north where Nazca Plate deposits are thicker (profiles 2-7; Fig. 7). The nature of the reflector is unknown; it may be a chert layer. The factors effecting sedimentation in this area are discussed in Rosato et al. (1974), Rosato (1974), and Kulm et al. (1974).

In the axis of the trench acoustic penetration of material identifiable as sedimentary fill is limited to slightly more than 1.0 sec. The 400 m regional bathymetric difference in trench axis depth discussed in the previous section is not an artifact of sediment thickness. Sediment thicknesses north of 7°40'S range from 0.2-0.3 sec on the seaward side of the trench axis to 0.8-1.0 sec at the continental slope-trench axis interface. In the southern province sediment thicknesses range from 0.25-0.5 sec to 0.7-1.1 sec from the seaward edge to the landward edge, respectively. The data show that the regional difference in water depth is due to a regional difference in depth of
the acoustic basement. The acoustic basement generally dips landward beneath the trench.

Sediment thicknesses in the basin B3 are difficult to measure on seismic reflection records taken at the southern end of the basin, because the basin is very narrow. To the north, however, where the basin is wider (Fig. 7; profiles 11-14), sediment thicknesses range from 0.12-0.4 sec. Sediment thicknesses in basins B1 and B2 are similar to those in B3, they range from 0.2-0.4 sec.

**Turbidite Deposition**

The sediments collected in this region are listed in Appendix I and shown in Figure 10. The cores are classified by physiographic area in Appendix II. Selected core lithologies and their approximate locations are indicated above the seismic reflection records (Figs. 13-22).

**Main Trench Axis**

Five of the seven cores in the trench axis consist of turbidites. Free-fall cores 80, 81, and 82 were taken immediately to the east at the interface between the continental slope and the trench axis and all contain turbidites. Cores 34 and 72 were taken in the main axis and contain turbidites. Core 3 has a water depth consistent with the trench axis but plots on the continental slope (Fig. 10). The position of the
Figure 10. Location of samples (see Appendix I). Hatchured area is main trench axis and turbidite basins.
core is considered to be in error since it was taken on a cruise prior to the advent of satellite navigation; the water depth indicates that the core came from the trench which lies 13 km to the west of the position given in Appendix I. The other core (79) which apparently does not contain turbidites, lies near the base of the continental slope.

Ridges

Cores 59, 64-67 were taken on the ridge R3 at 9°20'S (Fig. 10). Their lithologies have been discussed and uplift of the ridge is dated at less than 0.4 m.y. (Kulm et al., 1973b). Free-fall cores 64 and 65 and the multiple core from 67 each have a 3-5 cm cap of dark brown clay which is an oxidized surface layer. A sharp contact occurs between 16 and 19 cm in each of these cores and is interpreted as the graded basal contact of the most recent turbidite. Using a hemipelagic sedimentation rate of 1.7 cm/1000 yr (Prince et al., 1974), the maximum age of this most recent turbidite is 9000-11,000 yrs. B.P. and probably is considerably less than 10,000 yrs. This dates the uplift of the ridge at less than 10,000 years ago (Fig. 11). These young turbidites are clearly above the influence of turbidity current activity in the present trench axis.

Core 75 was taken on a topographic high in the trench axis (Fig. 15, profile 8) in an area where no sediment is visible on the seismic reflection record. It clearly contains turbidites.
A Turbidite core with maximum age of uplift in years before the present

- Ridge
- Basin
- Main trench axis

Figure 11. Location of major ridges and basins. Widths of basins are exaggerated. Important turbidite cores which show relative uplift are indicated.
Core 78 was taken on the seaward scarp of the trench axis on what appears to be an uplifted block or incipient ridge (Fig. 16; profile 9) elevated 300 m above the present trench floor. Both the piston core and the auxiliary gravity corer contain numerous silty sand laminations some of which are graded. These laminations are interpreted as turbidites. The clay mineralogy also indicates a terrigenous source (Rosato, 1974). Neither the piston core nor the multiple core have an oxidized hemipelagic cap, but the absence of an oxidized cap does not necessarily mean that the full section was not recovered. Generally the gravity corer is more likely to recover the surface sediment than the piston corer. The gravity core is used here to compute a maximum age for the uplift. The youngest silty lamination occurs at 9 cm below the surface giving a maximum age of 5300 yrs. B.P. for the turbidites and the corresponding uplift (Fig. 11). This is in good agreement with the results for core 77 which lies to the southwest of core 78. The absence of an oxidized cap in 76, 77, and 78 may be due either to the recent age of the last turbidite or to a difference in bottom conditions.

Basins

Four cores (60-63) were taken in basin B3 and the associated bathymetric low seaward of the ridge R3 just discussed (Fig. 7; profiles 11-19). Core 60 has a graded turbidite unit at the top, but no
hemipelagic cap. The multiple corer used as a trigger weight was lost when this core was taken. Cores 61 and 62 both have a thin cap of dark brown clay (3 cm and 0.5 cm, respectively). Core 61 has a sand lens at 90 cm and 62 has a graded fine sand to clay unit with a sharp lower contact at 58 cm. Using the 1.7 cm/1000 yrs rate for hemipelagic sedimentation, these cores yield maximum ages for the termination of turbidite deposition of 53,000 and 34,000 years, respectively (Fig. 11). A 34,000 yr. age is also indicated for core 63. Core 61 lies seaward of 62 and 63 near the scarp of the plate. Its apparent older age of uplift may be related to its more seaward position from the main axis. Similarly, the apparent older age for the termination of turbidity current activity in basin B3 than on ridge R3 may be related to its position seaward of the ridge (see Discussion section).

Gravity core 76 (the piston core had no recovery) lies in the same basin (B1) as core 77 and also contains turbidites (Fig. 10). Because of the extensive treatment of core 77 by Prince et al. (1974) little needs to be added here except to note that a northern source for the turbidites was suggested by them and is substantiated by the clay mineralogy (Rosato, 1974). Two large submarine canyons north and south of Lobos de Afuera (Fig. 4) funnel sediment to this area. Turbidity current deposition ended in this basin less than 5100 years ago (Prince et al., 1974). The present location of cores 77 and 76 is
700 m above the shallowest depth of the main trench axis (Figs. 4, 6, 10, and 11).

STRUCTURE

The true mystery of the world is the visible, not the invisible.

Oscar Wilde

The bathymetric and sedimentary evidence suggests recent deformation of the Nazca Plate and the trench turbidites. Evidence for deformation and tectonic movement also is seen in the seismic reflection records obtained in this area (Figs. 13-22). The unconformities and faults discussed in this section are shown schematically on the profiles of Figure 7. An analysis of the tectonism, fault patterns, and associated deformation is shown in Figure 23.

Main Trench Axis

Two types of deformation are indicated in the Peru Trench; they are gradational into one another. In the first, acoustic basement is block faulted down toward the continental slope (Fig. 12). Surface sediments are flat lying and may be down faulted toward the continent (Fig. 12). At depth the sediments are flat lying or dip toward the continent, but there is no indication of folding or uplift of the sediments or acoustic basement. In the second type, the axis is
Figure 12. Classification of acoustic basement beneath the trench axis and areas of deformation of surface sediments in the trench axis.
characterized by steeply dipping acoustic basement which is uplifted (Fig. 12). Folding and faulting of the sediments, both young and old, has occurred as a result of the uplift of acoustic basement (Fig. 12).

In the northern part of the study area there is little evidence of deformation. To the extreme north (profile 2) the turbidite fill is all flat lying and the basement is block faulted down toward the continental slope (Fig. 12). Farther south (profiles 3 and 4), the older turbidites show a very slight angular discordance with the younger flat lying trench fill. The older deposits have a very gentle apparent dip landward and the amount of discordance increases to the south. The basement here (profiles 3 and 4) is also faulted.

The buried ridge shown in profiles 5 (Fig. 7) and 24 (Fig. 13) may be a continuation of ridge R2 which plunges or is block faulted down into the main trench axis (profile 8; Fig. 15). Sediments are draped over this buried ridge and have a slight apparent dip toward the continental slope. Faults, which displace the older sediments but not the younger ones, are inferred on profile 5 seaward of the buried ridge but not on profile 24 which lies farther north. An inferred fault displaces the entire sedimentary section near the continental slope (profile 24, Fig. 13). The surface sediments in the trench on profile 6 (Fig. 7) and possibly on profile 7 (Fig. 14) dip landward but the tracklines do not extend far enough across the axis to determine whether the buried ridge is continuous between profiles.
Figure 13. Seismic reflection profile 24. See Figure 5 for location. B1, B2, B3 and R1, R2, R3 indicated on this and subsequent figures are basins and ridges, respectively, discussed in the text.
Figure 14. Seismic reflection profile 7. See Figure 5 for location.
5 and 8. The sediments in the main axis of the trench on profile 8 (Fig. 15) are too thin to see on the seismic reflection record but core 75 indicates that turbidites are present. A buried ridge similar to the one seen in profile 5 also occurs in profile 9 (Fig. 16). Here, however, there is no indication that the ridge has deformed the sedimentary fill. The sediment reflectors terminate abruptly at the ridge without deformation. The youngest horizontal reflectors truncate the older landward dipping reflectors (profile 9, Fig. 16). There is some suggestion that the surface sediment also dips landward, but this buried ridge does not show the same recent tectonism as do the ridges to the north.

Block faulting is evident on profile 10 (Fig. 7). Here, however, the sediment fill as well as the basement is faulted and the center of the axis is a graben (Fig. 12). The seaward side of the graben is bounded by a fault which extends from the surface into the basement. The fault along the landward boundary offsets the sediments, but does not appear to offset the basement. Between profiles 10 and 11 there are two trench crossings (X and Y in Fig. 12) which are not shown as profiles. The northernmost of these (X) has a block faulted basement with flat lying turbidites. The southern crossing (Y) has horizontal surface reflectors but at depth these reflectors are bowed up over two small highs in the acoustic basement. The basement is also faulted and the seaward edge of the turbidite fill has been faulted and uplifted.
Figure 15. Seismic reflection profile 8. See Figure 5 for location.
Figure 16. Seismic reflection profile 9. See Figure 5 for location. This crossing is broken at X into two figures. The section west of X is shown as Figure 22. Core lithology key applies to all cores shown in Figures 13-22.
slightly.

A transition between two ridges and two basins of broad, low relief to the north and a single peak of high relief and two narrow turbidite basins to the south (Kulm et al., 1973b) is shown in profiles 11-14 (Figs. 7, 17, 18, and 19). The lowermost reflectors in the main trench axis (profile 11; Fig. 17) have a slight apparent seaward dip (the only occurrence of an apparent seaward dip anywhere in the main axis); the middle reflectors are bent up against the ridge along the seaward edge of the axis and the uppermost reflectors are flat lying and show no signs of deformation. To the south (profile 12, Fig. 18) the landward basin has a thick flat lying undeformed sedimentary section overlying a section which dips gently landward. On profile 13 (Fig. 7) the upper turbidites are flat lying; the middle ones have an apparent offset that indicates a fault and the lowest reflectors are warped up against the ridge. The main trench axis deposits are faulted and the seaward side is uplifted and apparently tilted landward on profile 14 (Fig. 19). In this region ridge R3 may be a series of en echelon fault blocks plunging northeast and intersecting the axis at a low angle (Fig. 23). Differential movement along the faults separating these blocks could account for the varying degrees of deformation observed in the sediments. The seismic records over basin B3 (profiles 12 and 13; Fig. 18) indicate a probable discordance between older more steeply landward dipping sediments and gently
Figure 17. Seismic reflection profile 11. See Figure 5 for location.
Figure 18. Seismic reflection profile 12. See Figure 5 for location.
Figure 19. Seismic reflection profile 14. See Figure 5 for location.
dipping surface sediments. The surface sediments dip more steeply to the north (profile 12) than to the south (profile 13) which indicates more relative recent motion to the north. Farther south the turbidite fill in the basin B3 apparently is undeformed (profile 14; Fig. 19).

No seismic records exist for profiles 15 and 16 (Fig. 7); a narrow landward basin and a broader seaward basin with a low relief ridge in the center of the seaward basin (B3) occur here. Five kilometers to the south, the seaward basin is narrow with flat lying deposits which may form a slight angular unconformity with the landward dipping deposits below; the dip increases down section (profiles 17 and 18; Figs. 7 and 20). All reflectors terminate abruptly against the ridge (R3) except on profile 18 where the reflectors below the angular unconformity are bent up along the ridge R3 (see Kulm et al., 1973b, Fig. 2). Farther south the seismic record is too poor over basin B3 to see the orientation of the reflectors. The turbidite fill in the trench axis is faulted and tilted landward. Again the apparent dip increases with depth.

Acoustic basement dips steeply beneath the trench axis in the vicinity of the ridge R3 (Figs. 17-20). If the basement is offset by faults, the faults are obscured by hyperbolae.

Three areas display horizontal turbidites with a possible gentle seaward onlap (Figs. 12 and 21). Trench sediments are flat lying throughout most of the section on profile 21 with a slight downbowing
Figure 20. Seismic reflection profile 17. See Figure 5 for location. See Figure 16 for core lithology explanation.
Figure 21. Seismic reflection profile 20. See Figure 5 for location.
in the oldest deposits. A fault downthrown toward the continent extends through the most recent deposits on the seaward side of the axis, but the sediments on either side of the fault scarp are flat lying. The basement appears to be block faulted beneath the axis on profile 21 and possibly on profile 20 (Fig. 12).

**Basins and Ridges**

In this area, the basins occur at greater depths than the regional Nazca Plate depth (Fig. 9). There has been significant deformation and movement in these basins (Fig. 11). At the northern end of basin B1, horizontal surface sediments unconformably overlie landward dipping reflectors (profiles 8 and 9; Figs. 7 and 15). To the south (profile 10) all the sediment in basin B1 is flat lying and there are no indications of deformation in the basin. Seaward of basin B1, there is a small downfaulted basin B4 which may contain turbidites but which was not sampled. It parallels basin B1 and shows the same pattern of deformation as B1 (Fig. 7).

Basin B2 shows a different pattern of deformation from that in basins B1 and B4. To the extreme north (profile 8, Fig. 15), there is deformation of the sediment fill which indicates relative uplift of the ridge R2. The surface sediments dip seaward slightly and older fill is downfaulted toward the center of the basin. Toward the south (profile 9; Fig. 22), the surface sediments are flat lying while the
Figure 22. Seismic reflection profile 9. See Figure 5 for location. See Figure 16 for core lithology explanation.
older sediments dip gently landward but not as steeply as in basin B1 (Fig. 22). To the extreme south (profile 10; Fig. 7), the surface sediments in the basin B2 dip seaward but the older sediments are horizontal.

Basins B1 and B4 have a similar tectonic history, but basin B2 does not, which indicates that basins B1 and B2 are not being deformed by the same tectonic motions and must be separated by one or more major faults (Fig. 23). Hussong et al. (1973) found evidence of deep crustal offsets at 8°30'S (profile 10) from seismic refraction data.

The ridges are bounded by faults. The nature of these faults and the origin of the ridges is discussed in the following section.

The Nazca Plate is highly faulted (Fig. 7). The orientation of a fault is impossible to determine from a single seismic reflection record. The present data, therefore, are not sufficient to unambiguously interpret the fault pattern. One interpretation is offered which is consistent with the data, where faulting is assumed to parallel regional bathymetric trends (Fig. 23). Areas of relative uplift and relative subsidence are also indicated on Figure 23.
Figure 23. Tectonic map showing major faults and areas of relative uplift and subsidence.
DISCUSSION

If the world were good for nothing else, it is a fine subject for speculation.

William Hazlitt

General Imbricate Thrust Model

Several features of the structure of the trench and the continental margin suggest that imbricate thrusting may be an important tectonic mechanism in this region. The general mechanism as envisioned by other authors is outlined briefly below. The discussion is then expanded in light of the structures observed in this study.

Seely et al. (1974) and Kulm and Fowler (1974) in independent studies have found evidence for continental accretion by imbricate thrusting at convergent plate boundaries (Fig. 24). These thrust sheets appear to involve the sedimentary layer and possibly the upper part of the basaltic layer. Imbricate thrusting beneath the continental slope causes uplift of the continental slope and shelf edge and subsidence of the area landward of the shelf edge (Seeley et al., 1974; Fig. 24). Such a mechanism would explain the shelf-break structural high frequently observed along continental margins. Old imbricate thrust sheets often create benches along the lower and upper continental slope (Kulm and Fowler, 1974; Seely et al., 1974). These then are the general characteristics of imbricate thrusting observed
Figure 24. Imbricate thrust model showing orientation of older imbricate thrust sheets and benches on the continental slope. This figure is generalized and does not specifically represent the area of this study.
landward of the trench. To date no one has shown evidence nor outlined the mechanics for the formation of these imbricate thrusts in the area of the trench.

At this general level, observations made along the Peru-Chile arc show agreement with the imbricate thrust model. Imbricate thrusting has been proposed for the Nazca Plate at 12°S on the basis of seismic refraction work (Hussong et al., 1973). Hussong et al. (1973) find evidence that the oceanic crust is underthrusting itself about 250 km seaward of the present trench axis and note that "although not well-defined, the velocity configuration under the continental slope is not inconsistent with imbricate thrust fault structure" (Hussong et al., 1973, p. 221).

Shallow earthquakes occur beneath the continental slope, but above the depth of the Benioff Zone along the west coast of Peru (Santo, 1969). Some of these earthquakes may be caused by motions along old imbricate thrust faults. In the area 7°-12°S off South America, a basement high of Paleozoic and possibly Precambrian rocks occurs beneath the outer shelf (Kulm et al., 1973a). A broad synclinal basin lies between the Paleozoic high and the shoreline and probably consists of Cenozoic and Mesozoic marine sediments similar to those found in the coastal region. Pflaker (1972) documented uplift of the area between the trench axis and the edge of the continental shelf and subsidence of the continental shelf for the Chile margin at
Benches occur on the lower continental slope off Peru and are postulated to be old imbricate thrust sheets (Fig. 24). The fact that these benches are not all horizontal and continuous along the continental slope, but plunge north and south and are discontinuous along the continental slope suggests that past imbricate thrust sheets did not form simultaneously along the entire length of the trench.

Imbricate thrusting at convergent plate boundaries requires lateral compression in the direction of thrusting. Intraplate earthquakes are relatively rare, but Sykes and Sbar (1973) in a worldwide study found 30 intraplate earthquakes which were characterized predominantly by thrust faulting and which indicated compression of the lithospheric plates in the direction of plate motion. A focal mechanism in the middle of the Nazca Plate indicates compression within the Nazca Plate in the direction of plate motion toward the Peru Trench (Mendiguren, 1971). Several other earthquakes examined by Mendiguren had insufficient data to determine focal mechanism solutions, but were consistent with compression of the Nazca Plate. Goebel (1974) found that the Nazca Plate thickens toward the trench at 12°S. He attributed this thickening to lateral compression of the Nazca Plate in the direction of plate motion.

Earthquakes in the area of trenches and beneath continental slopes have both compressional and extensional first motion solutions
(Stauder and Bollinger, 1963; Isacks and Molnar, 1971; Abe, 1972; and Huaco, 1973). The tectonics are considerably more complex in the vicinity of the convergent boundary than in the middle of the plate and are not well understood. Extensional motions (e.g., the subsiding basin landward of the shelf edge) as well as compressional motions are possible in the imbricate thrust model.

**Development of Thrusting in the Trench Axis**

Several facts must be considered in any interpretation of the tectonic framework of the trench. First, recent deformation of the acoustic basement and the overlying turbidite fill is seen in the axis of the trench. This deformation is most intense at 7°40'S and 9°20'S, and produces uplifted ridges and sediments and faulted and tilted sediments. At 9°20'S, relative uplift appears to have migrated landward across the trench axis.

Second, the trench changes trend from northwest to northeast between 0°-10°S, as do the adjacent Andean Mountains (Fig. 1). This change in trend occurs as a series of short straight segments (Fig. 25). The trench axis changes trend from N11W (segment 1) to N24W (segment 2) to N31W (segment 3). Segment 2 (Fig. 25) is the only complete segment in this region and has a length of 180 km. Maximum deformation occurs where the axis changes trend (Figs. 12 and 23). Major tear faults are postulated at these inflection points.
Figure 25. Classification of stages of development in imbricate thrust model as shown in Figure 26. Changes in trend of the main trench axis. Dashed lines are extensions of the trench segments drawn to facilitate seeing the slight changes in trend.
Kulm et al. (1973) have shown that the ridge at 9°20'S is a structural feature that originated in the trench axis. Although the age of the basalt (8.7 m.y.) suggests mid-plate volcanism, the presence of turbidites on top of the ridge requires that the elevation of the ridge take place after both the turbidite deposition (<10,000 BP) and the volcanism. If mid-plate volcanism did occur, it probably was associated with a structurally weak point or lineament which may be the lineament along which the fault bounding the seaward scarp of the ridge has formed.

The presence of a ridge in the axis of a trench is not unique to the northern Peru trench. A similar double trench separated by a ridge occurs in the eastern Mediterranean (Ryan et al., 1973). Underthrusting of the European plate to the north by the Mediterranean plate to the south is postulated on the basis of earthquake data (Papazachos and Comninakis, 1971). The more southerly Strabo trench is the 'outer trench'. It is narrow with little sediment visible on seismic reflection records and has a steep inner wall (the northern wall of the trench). This inner wall is the seaward scarp of the 'ridge', the Strabo Mountains (Ryan et al., 1973). North of the Strabo Mountains lies the inner Pliny trench. It is broader and deeper than the Strabo trench and has a thick gently dipping sedimentary section (Wong et al., 1971). Site 129B in the axis of the Strabo trench (Deep Sea Drilling
Project) recovered lithic graywacke sandstone with abundant metamorphic and volcanic rock fragments which indicate a northern "island arc source region with downslope access to the Mediterranean Ridge. Today such access is completely blocked by the Strabo Mountains" (Ryan et al., 1973, p. 343). Uplift of the Strabo Mountains has occurred since the Late Pliocene (Ryan et al., 1973). The structural and historical similarities between this region and the northern Peru trench suggest that a common tectonic mechanism may be involved.

A model for the development of imbricate thrust sheets that involves the basement in the axis of the trench is shown in Figure 26. The portion of the oceanic plate near the subduction zone is bent downward toward the trench. Superficial normal faults form as the result of tension along the line of flexure in the oceanic plate. When this same piece of oceanic crust reaches the axis of the trench, its upper surface is no longer under tension, but is now under compression (Fig. 26A). If motion along subduction zones is viewed as episodic, then it is possible for compressional stress to build up in the oceanic plate during times of slowed subduction. This increased compressional stress may cause bulging up of the plate at the trench axis. When rupture and underthrusting takes place, the trench subsides again. When the compressional stress is enough to overcome friction along the normal fault, movement will occur. The normal faults represent lines of weakness. Motion will most likely occur
Figure 26. Model for formation of imbricate thrust sheets in the axis of the trench.

A. Normal faulting, flat lying trench fill.
B. Graben structure, uplift of seaward edge of trench by reverse faulting.
C. Transition from reverse fault to thrust fault, buried ridge.
D. Thrust fault developed, ridge in axis.
E. Thrust sheet moves forward and is accreted to lower continental slope.
along these faults, but because the stress applied is now compression-
al rather than extensional the motion will be reversed. These reverse
faults cause uplift of the seaward edge of the trench axis (Fig. 26B).
If the compressional stress is large enough and is not sufficiently
relieved by reverse faulting a thrust fault will form (Figs. 26C and
26D). Motion occurs along the old as well as the new thrust fault.
The older uplifted piece of oceanic crust is thrust forward and at the
same time it is accreted to the bottom of the continental slope (Fig.
26E).

The structure of the Peru trench has been classified according
to its stage of development in the imbricate thrust model (Fig. 26).
In plan view it appears that the development of imbricate thrusting is
most advanced at two points corresponding to profile 8 and profile 17
(Fig. 25), and that as one proceeds north and south from these two
points, the amount of visible imbricate thrusting decreases.

The ridge R3 at 9°20'S in the axis of the trench is thought to be
an imbricate thrust sheet. A highly exaggerated profile of the ridge
is deceptive. For comparison profile 14 is shown as it appears in
Figure 7 with a 13:1 vertical exaggeration and with no vertical
exaggeration (Fig. 27). With no vertical exaggeration, ridge R3
looks more like a thrust sheet. The maximum age of uplift indicated
by the turbidites on ridge R3 and in basin B3 suggests a landward
migration of uplift in the trench (Sediments Section). The model set
Figure 27. Effect of vertical exaggeration on ridge geometry. Ridge R3 is considered part of an imbricate thrust sheet and is shown at zero exaggeration for comparison with the high vertical exaggeration of Figure 7 (13:1).
forth in Figure 26 is consistent with this landward migration of uplift.

Frank (1968) showed that unless the dip of the subduction zone exactly equals one-half of the radius of curvature (in degrees) of the trace of the trench axis, the subducted plate will undergo either lateral compression or extension. Many authors have postulated segmentation of the subducted oceanic plate from earthquake studies and from correlations with continental features (Isacks and Molnar, 1971; Stoiber and Carr, 1971; Carr et al., 1973; Lowrie and Stover, 1973; Stauder, 1973). Carr et al. (1973) estimate that the width of one of these segments ranges from 100-300 km. Stauder (1973) postulates such segmentation of the Nazca Plate and suggests that the various segments may be absorbed differentially.

The tear faults postulated at the trench inflection points are similar to those postulated for the segmentation model of Carr et al. (1973). The thrust sheet segments should not be viewed as rigid because faulting and deformation occur throughout the entire length of individual segments (Fig. 23).

One way in which various segments of a subducted oceanic plate may be absorbed differentially is by subduction at different rates. Silver (1971) postulated differential subduction off Oregon and Washington on the basis of magnetic anomalies in the Gorda Plate. Differential spreading can presumably cause differential subduction. Using an imbricate thrust model, differential subduction can be achieved
even without differential spreading.

First, a distinction needs to be made between convergence rate and trench subduction rate. Convergence rate is a measure of how fast two fixed points in the center of each of the two lithospheric plates approach each other. Trench subduction rate is the rate at which oceanic material is underthrusting the continent at the continental slope-trench axis interface. In the imbricate thrust model, these two rates are not necessarily equal. If the convergence rate is 10 cm/yr for the Nazca Plate and South American block (Minster et al., 1974), then the convergence rate will be 10 cm/yr everywhere but the trench subduction rate can range from 0-10 cm/yr. When motion occurs along old imbricate thrust sheets, the trench subduction rate can be lower than the convergence rate (Fig. 28). Pflaker (1972) postulated such a motion from his study of the 1964 Alaska earthquake and the 1960 Chile earthquake. When thrusting occurs along older imbricate thrust faults, the oceanic plate at the trench axis does not underthrust the lower continental slope; the upper continental slope overthrusts the lower continental slope and direct subduction of the oceanic plate (minus sediments) occurs only beneath the continental shelf and farther inland (Fig. 28). Thus, by using varying amounts of motion along old imbricate thrust faults beneath the continental slope, a mechanism for differential subduction is achieved.
Figure 28. Schematic diagram showing how imbricate thrusting occurring along old imbricate thrust faults causes overthrusting of the lower continental slope by the upper continental slope. Cross hatched area shows net displacement of upper continental slope.
Structural Features on the Adjacent Nazca Plate

Three primary factors are considered to be important in the initiation of thrust faulting: 1) the orientation of the trench with respect to the direction of convergence, 2) the structure which the oceanic plate acquired upon formation and prior to its arrival at the convergent plate boundary, and 3) the crustal structure of the continental lithospheric plate. The first factor has been discussed already, the second is discussed here and the third is discussed in the last section.

The most prominent structural features on the Nazca Plate are the possible fracture zone and basins B1 and B2 (Fig. 8). The apparent fracture zone is almost certainly a feature acquired upon formation of the Nazca Plate. It is not at all clear, however, whether the basins B1 and B2 are old features of the oceanic plate or whether their origin is associated with the tectonics of the converging plate boundary. The basins do appear to be the result of faulting. This is suggested by this study and by postulated deep crustal faults based on seismic refraction work (Hussong et al., 1973).

There are several lines of evidence which suggest that basins B1 and B2 are the eastward extension of the apparent fracture zone (Fig. 8). On the topographic profiles (Fig. 7) the dimensions of the basins B1 and B2 are similar to those of the apparent fracture zone.
Sharp regional depth differences, similar to the one noted in this area, most commonly occur across a fracture zone. The 400 m offset in acoustic basement in the trench axis occurs where basins B1 and B2 intersect the trench axis. There are no other topographic features east of profile 22 which are indicative of a fracture zone (Fig. 8).

If the basins are the eastward extension of the fracture zone, two possibilities arise. First, if the present orientation of the apparent fracture zone was established when the plate formed, then the abrupt change in trend requires a change in spreading direction. Second, if the present orientation is not due to a change in spreading direction but is the result of the interaction of the oceanic plate with the trench, then fracturing and rotation of the section of the ocean floor around the basins is required. This rotation would also require the bulging up of the plate and/or intraplate thrusting west of the hinge point and spreading apart of the plate between the fracture zone -- basins and the trench axis. The evidence is not sufficient to substantiate either possibility.

The fracture zone immediately to the north at 5°15'S trends N45E at its intersection with the trench. This suggests that basins B1 and B2 do not represent a fracture zone, but rather the oceanic plate has been fractured along a shear fault. Silver (1971) postulates such a shear fault with an offset of 70 km on the Gorda Plate. The problem again is that transverse motion along this fault would require
the opening of the oceanic plate or intraplate overthrusting; there is no evidence to support this interpretation.

A final possibility is that the basins occur along the fault plane of a new imbricate thrust sheet. The recent uplift at core sites 76, 77, 78 (Fig. 11) seems to argue for this interpretation. The turbidites in the basins, however, predate this most recent uplift and make the existence of the basins as a topographic low necessary prior to the most recent tectonism at 5100 BP. Also, although a refraction profile across these basins suggests deep crustal fractures, the fractures do not extend to the mantle as they do at 12°S (Husson et al., 1973). Basins B1 and B2 therefore do not appear compatible with the incipient thrust model, at least as proposed for the oceanic crust at 12°S.

The evidence then is insufficient to make a definitive interpretation. The possibility that the oceanic plate is underthrusting itself along the line represented by the basins B1 and B2 seems very plausible. It leaves unanswered the question of why a thrust fault should form at that particular point and that particular orientation. I personally feel that the basins formed along an older feature that predates the tectonism in the trench and that this older structure has been a major factor in determining the tectonics of the trench area. I suggest that the change in trend of the trench axis and 400 m offset in the trench axis at 7°40′S are for the most part the result of the
structural line of weakness represented by the basins B1 and B2.

In keeping with the model proposed in Fig. 26, it is postulated that subduction of the oceanic plate on segment 1 (Fig. 25) was stopped or slowed sometime prior to 5,100 yrs. B.P. and that the acoustic basement beneath the trench axis was higher than at present. This higher acoustic basement which may have been caused by bulging up of the compressed plate (Figs. 26a and 26b) allowed turbidity currents to spill out into topographic lows on the Nazca Plate (i.e., basins B1 and B2). Approximately 5100 yrs. B.P. the trench reactivated and thrust faults (Fig. 26) cut off the turbidity current supply to basins B1 and B2 by lowering the acoustic basement. The present difference in depth between the main axis and basins B1 and B2 is 700 m. The absolute motion is unknown, but was probably a combination of subsidence of the trench axis and uplift of the Nazca Plate in the area of basins B1 and B2.

**Regional Tectonic Relationships**

Without comparable studies from other areas of the Peru-Chile Trench and the adjacent South American continent, it is not possible to determine conclusively the relationship between the structure of the trench and the structure, seismicity, and volcanism on the adjacent continent. The following observations are offered as the author's present speculations on the nature of this relationship.
The seismic gaps (Fig. 2), which represent areas where there is an absence of large magnitude shallow earthquakes, show a good correlation with the inflection points in the Andean structural trends. It is postulated that the seismic gaps are due to extensively fractured material in the subducted oceanic plate. The trench axis in the area studied is irregular in curvature and cannot be described as a segment of a single circle. Because the trench between 6°-10°S does not satisfy the geometric relationship described earlier (Frank, 1968), it is presumed to be deformed both before and after subduction. The highly deformed and faulted nature of the subducted material may preclude the build-up of the large stress fields necessary for a large magnitude earthquake.

The lack of recent vulcanism in the area of the Huancabamba Deflection may be partially due to the apparent dominance of active imbricate thrusting in this region. The most easily magmatized and mobilized portions of the subducted plate are the sediments and the upper weathered portion of the basaltic layer 2. These materials are accreted to the continental slope and are not being subducted to sufficient depths to generate igneous activity.

Finally, there seems to be a correlation between the trend of the Andes Mountains and the trend of the Peru Trench. The Peru-Chile Trench parallels the Andes Mountains throughout its entire length (Fig. 1). One possible interpretation is that the position of the
Andes Mountains is controlled by the dip of the Benioff Zone and hence indirectly by the location of the trench. The data in this study, however, are not inconsistent with the converse idea, that the position of the present trench is controlled by the location of the Andes Mountains. This study suggests that by the mechanism of imbricate thrusting a trench can migrate or remain stationary. Because convergent motion is not only accomplished along the oceanic plate-continental plate boundary, but can also be brought about by continental overthrusting along old imbricate thrust faults, a trench can also be an episodic feature. This mechanism permits trenches to change their configuration to conform to the crustal structure of the overriding continental plate and provides a mechanism for complex histories such as the one observed for the trench in this study area.

CONCLUSIONS

(1) The axis of the Peru Trench undergoes a significant change in trend at 7°40'S and at 9°20'S.

(2) The oceanic plate (Nazca Plate) is fractured into three segments in this area (N11W, segment 1; N24W, segment 2; and N31W, segment 3) which are being subducted at slightly different angles. These segments are separated by tear faults which occur at 7°40'S and at 9°20'S.

(3) Recent deformation of the acoustic basement and the overlying
turbidite fill is seen in the axis of the Peru Trench. This deformation is most intense at 7°40'S and 9°20'S and takes the form of uplifted ridges with turbidites on top, and faulted and tilted sediments.

(4) Imbricate thrusting has recently been initiated at the boundaries between these three segments at 7°40'S and 9°20'S in the axis of the trench and has caused the faulting and uplift of the acoustic basement and the overlying turbidites.

(5) The origin of the uplifted basins B1 and B2 on the seaward wall of the trench is unknown but is thought to pre-date the tectonic motions associated with the trench. The location of the 400 m offset in the basement beneath the trench and the change in trend of the axis at 7°40'S is, therefore, in large part due to the presence of the structural line of weakness represented by basins B1 and B2.

(6) Turbidity current deposition in basins B1 and B2 ceased 5100 yrs. B. P. when thrust faulting reactivated the trench axis at 7°40'S and caused a 700 m displacement of the trench relative to the basins.
BIBLIOGRAPHY


APPENDIX
## APPENDIX I. Deep-sea Cores: Sampling Data and Sediment Description

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1 SIO = Scripps Institute of Oceanography  
FSU = Florida State University (Eltanin cruise)  
HIG = Hawaii Institute of Geophysics  
LDGO = Lamont-Doherty Geological Observatory  
DISC = British Discovery Expedition (1925-1933)  
OSU = Oregon State University

2 CP = piston core; FF = free-fall core; MG = multiple gravity core;  
CV = von Herzen core; CG = gravity core
# APPENDIX II. Deep-sea Cores: Physiographic Location

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<th>Main Trench Axis</th>
<th>Ridges</th>
<th>Basin B1</th>
<th>Oceanic Plate</th>
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<td>68 73 N</td>
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<td>34 5845 T</td>
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<td>72 5846 T</td>
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<td>80 6117 T</td>
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<tr>
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<td>130 5500 N</td>
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<td>75 5670 T</td>
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<tr>
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<td>63 5821 T</td>
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</tbody>
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Left column: sample number
Middle column: water depth in meters
Right column: T = Turbidites
             N = No turbidites