AN ABSTRACT OF THE THESIS OF

Juan Antonio Masias Echegaray for the degree of Master of Science
(Name) (Degree)

in Oceanography presented on 6 June 1975
(Major) (Date)

Title: MORPHOLOGY, SHALLOW STRUCTURE, AND EVOLUTION OF THE PERUVIAN CONTINENTAL MARGIN, 6° TO 18°S

Abstract approved: Redacted for Privacy
L. D. Kulm

Detailed bathymetric survey data were collected along the Peruvian continental margin and were compiled by the author and other investigators to construct a new bathymetric map for the area between 6° to 18°S latitude. Based on this map and individual bathymetric profiles, the continental shelf topography is essentially flat. Four different physiographic provinces (A-D) are defined on the continental slope. Each province apparently reflects the structural and tectonic settings in a given area. The trench is separated into three provinces on the basis of regional depth differences.

Three sedimentary basins, Sechura, Salaverry, and Pisco, are recognized on the Peruvian continental shelf between 6° to 15°S. The landward migration on the axis of deposition within these basins is interpreted to be the sedimentary response to tectonism (uplift) taking place along the outer edge of the continental margin. Prominent

sedimentary basins also occur on the upper continental slope; these basins have been named with respect to their geographic position as the Lima and Arequipa Basins. Landward and seaward migration of the axis of maximum deposition in these basins is interpreted to be the result of variable rates of uplift along the outer margin. Uplift along the seaward edge of these basins suggests that the accretion of trench and oceanic plate deposits is taking place along the lower and middle continental slope.

Seismic reflection profiles, extrapolation of regional structural trends onshore to offshore along the Peruvian margin, and positive free-air gravity anomalies off southern Peru (Whitsett, 1975), show that an outer continental shelf high is present off northern and central Peru. This high is believed to be composed of Paleozoic rocks with a possible Precambrian core. The high is linked with the Amotape Mountains in northern Peru and the Coastal Ranges in southern Peru. It is an important element in the development of the Peruvian continental margin.

Using all of the data available, a four stage model is proposed for the Mesozoic-Cenozoic evolution of the Peruvian continental margin. Stage I describes conditions prior to the formation of the subduction zone during Triassic time. Plate collision is postulated at the beginning of Stage II with the formation of a Benioff Zone about 180 m.y. ago (Triassic-Jurassic boundary). Accretion of trench and oceanic plate deposits occurs as a result of the initiation of underthrusting of the South America Block by the Nazca Plate. Stage III describes the continuous seaward growth of the continental slope during middle to late Cretaceous time. During late middle (Turonian) and middle late Cretaceous (Santonian) time diastrophism in southern Peru restricted the marine conditions to central and northern Peru. During late Cenozoic time (Stage IV) the Peruvian margin attained its present configuration through continuous seaward growth of the continental slope and buildup of the sedimentary sequences found in the Sechura, Salaverry, and Pisco Basins, in central and northern Peru. Late Cenozoic volcanism in southern Peru is apparently associated with the large amount of sediments that reached the southern Peru Trench since late Cretaceous time. The Nazca Ridge apparently approached the Peruvian continental margin during Cenozoic time, and locally changed the morphology of the continental slope. The proposed model shows that the Peruvian continental margin is growing seaward and that continental erosion of the crystalline continental block is not necessary along the Peruvian continental margin. The model explains and justifies the presence of the outer continental shelf high off northern and central Peru.

Morphology, Shallow Structure, and Evolution of the Peruvian Continental Margin, 6° to 18°S

by

Juan Antonio Masias Echegaray

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1976

APPROVED:

Redacted for Privacy

Professor of Oceanography
in charge of major

Redacted for Privacy

Dean of School of Oceanography

Redacted for Privacy

Dean of Graduate School

Date thesis is presented 6 June 1975

Typed by Margie Wolski for Juan Antonio Masias Echegaray

ACKNOWLEDGEMENTS

I am particularly grateful to Dr. L. D. Kulm for his guidance and patience in deciphering what I was trying to say or write through my Peruvian English. His encouragement during my work is deeply appreciated.

I wish also to thank the other members of my committee, Drs. K. Oles, S. H. Johnson, and E. J. Dasch. Roger Prince and William Schweller provided me with computerized data and were the source of practical suggestions and clarifying discussions. Mrs. Margie Wolski did a nice job typing the manuscript.

I thank Geny and Patty for sharing in the ups and downs during my graduate career. Finally I thank Juan and Marta for their years of patience, trust and encouragement.

Special thanks are due to Petroleos del Peru, Gerencia de Area Exploracion-Produccion and the Departamento de Geologia for providing financial support during my studies at Oregon State University. The data for this study were collected under the support of the National Science Foundation through the International Decade of Oceanic Exploration, Nazca Plate Project (Grant GX-28675).

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MORPHOLOGY, SHALLOW STRUCTURE AND EVOLUTION OF THE PERUVIAN CONTINENTAL MARGIN, 6° TO 18°S

INTRODUCTION

The Peruvian continental margin is located along the western part of the South American continent. It is bounded on the west by the oceanic Nazca Plate and on the east by the Peruvian coast, the Coastal Range and the foothills of the Andean Cordillera. The area of this study lies between 6° and 18°S latitude (Fig. 1).

According to the plate tectonic concept, the western margin of South America is one of the best examples of continental plate-oceanic plate collisions. Consequently, the Andean Cordillera has become the typical example of a fold belt developing at the edge of the continental plate by the processes of subduction. Variations in the structure, sediment distribution, volcanism, seismicity on the continental slope and in the trench and orogenesis of the Andean Cordillera are interpreted to be the likely consequence of this collision.

Detailed studies of the Peruvian continental margin do not have a long history and were often included in regional studies of the western part of the South America continent. A study of the distribution of earthquakes (Benioff, 1954) established the presence of the Benioff Zone. The Peru-Chile Trench was described later by Zeigler *et al*. (1957) and Fisher and Raitt (1962), with later contributions to

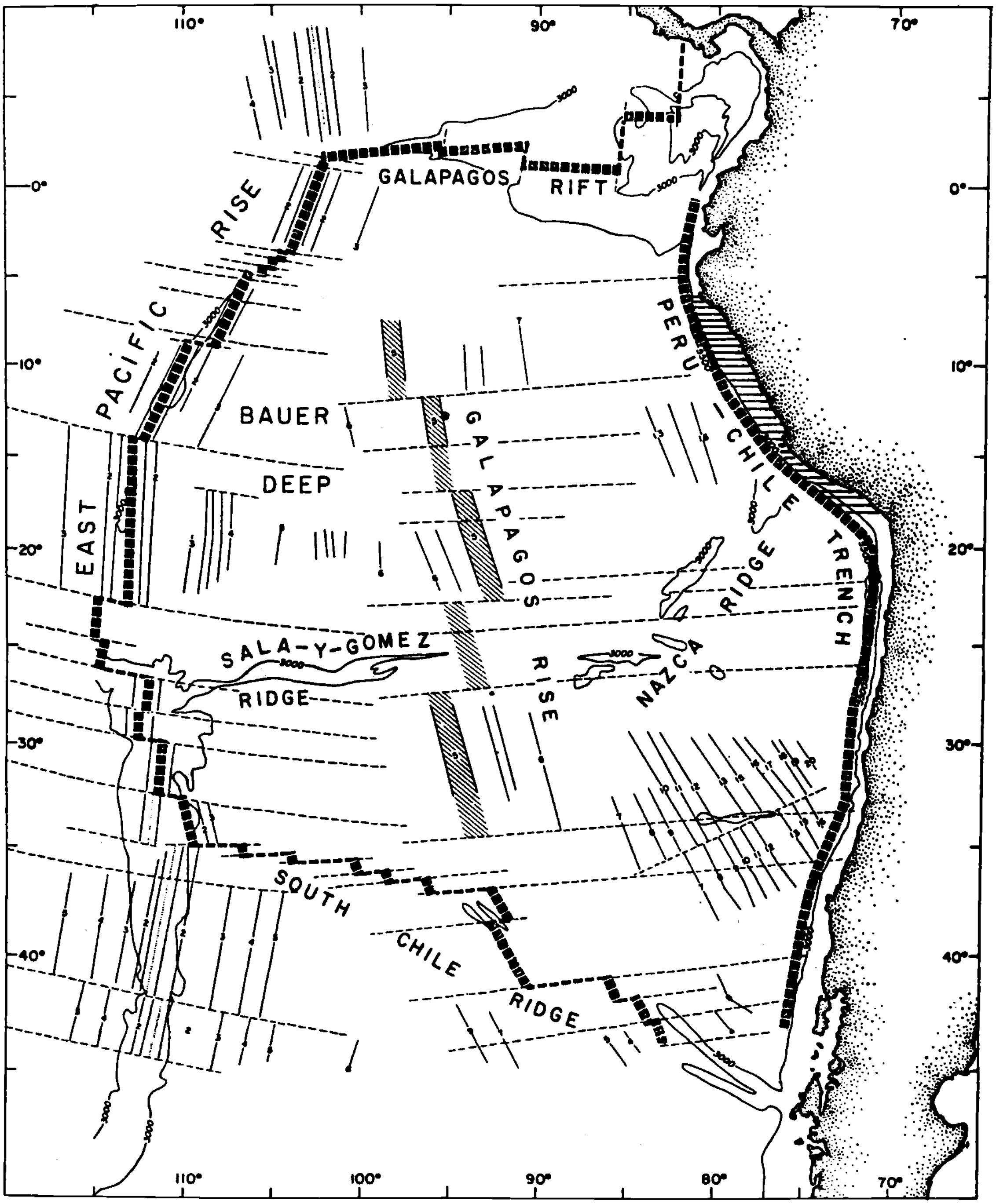


Figure 1. Location map. Magnetic anomalies and features modified from Herron (1972).

the knowledge of the continental margin of western South America by Hayes (1966, 1974); Herron and Hayes (1969); Scholl et al. (1968, 1970); James (1971); Stauder (1973, 1975). Until the present study, no one has made regional correlations of significant geologic events along the margin and continent.

The Nazca Plate and Peruvian continental margin have been under intensive study since 1971 through the joint investigations of Oregon State University (OSU), Hawaii Institute of Geophysics (HIG), and Pacific Oceanographic Laboratories (NOAA) with cooperation by various Peruvian scientists. Several papers and abstracts (Kulm et al., 1973, 1973a, 1974, 1975; Rosato, 1974; Prince, 1974; Prince and Kulm, 1975; Johnson et al., 1975; Couch and Whitsett, 1975), that deal with the structure and sediments of the Nazca Plate and Peruvian margin, have been published and these results will be incorporated into the present study at the appropriate place.

The study described here was undertaken to examine the broad framework of the Peruvian margin and, if possible, to relate this to plate tectonic theory. The main objectives of this study are to: (1) determine the morphology and shallow structure of the Peruvian continental shelf and continental slope; (2) determine the presence and extent of sedimentary basins along the margin; (3) extrapolate the onshore geology into the offshore region; (4) determine the relationship of structure and morphology to tectonism and sedimentation along the margin; and (5) present a model for the Mesozoic-Cenozoic evolution of the Peruvian continental margin.

From the present study it is clear that major new efforts need to be devoted to further study of the Peruvian continental margin. New seismic reflection techniques and data processing will be required to investigate the nature of the sediments and crustal rocks underlying the continental margin and trench.

METHODS

The geophysical data used in this study were collected by the R/V Yaquina of OSU on cruises in 1972 and 1974 and by the R/V Kana Keoki of HIG on cruises in 1972.

Bathymetric and shallow seismic reflection data were taken with 12.5 and 3.5 kHz sources, respectively. Deep seismic reflection records were made using various sized air guns, a single channel hydrophone streamer, and amplifiers and recorders. Filter settings were generally 40 Hz (low cut) and 120 Hz (high cut). The seismic data were recorded on an EPC graphic recorder with a 4 sec sweep rate.

Twenty-six tracklines were used in this study (Fig. 2). Additional tracklines were used to construct the bathymetric map of the Peruvian margin, but are not shown here. The bathymetric map was compiled in sections by Roger Prince (1974), 6° to 10°S; the author from 10° to 13°S; and Gordon Ness and R. Prince from 13° to 18°S. The entire map is presented here (Fig. 3).

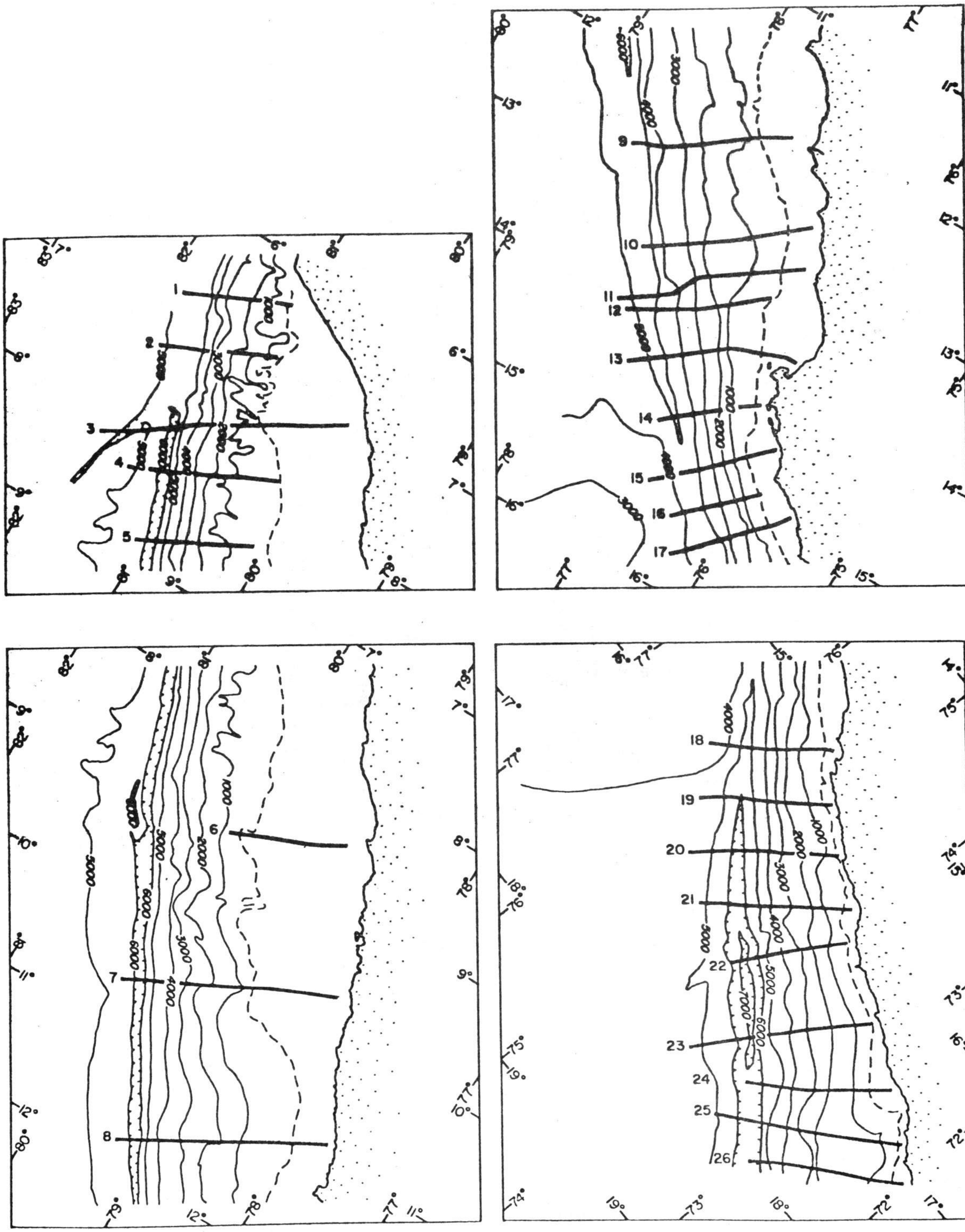
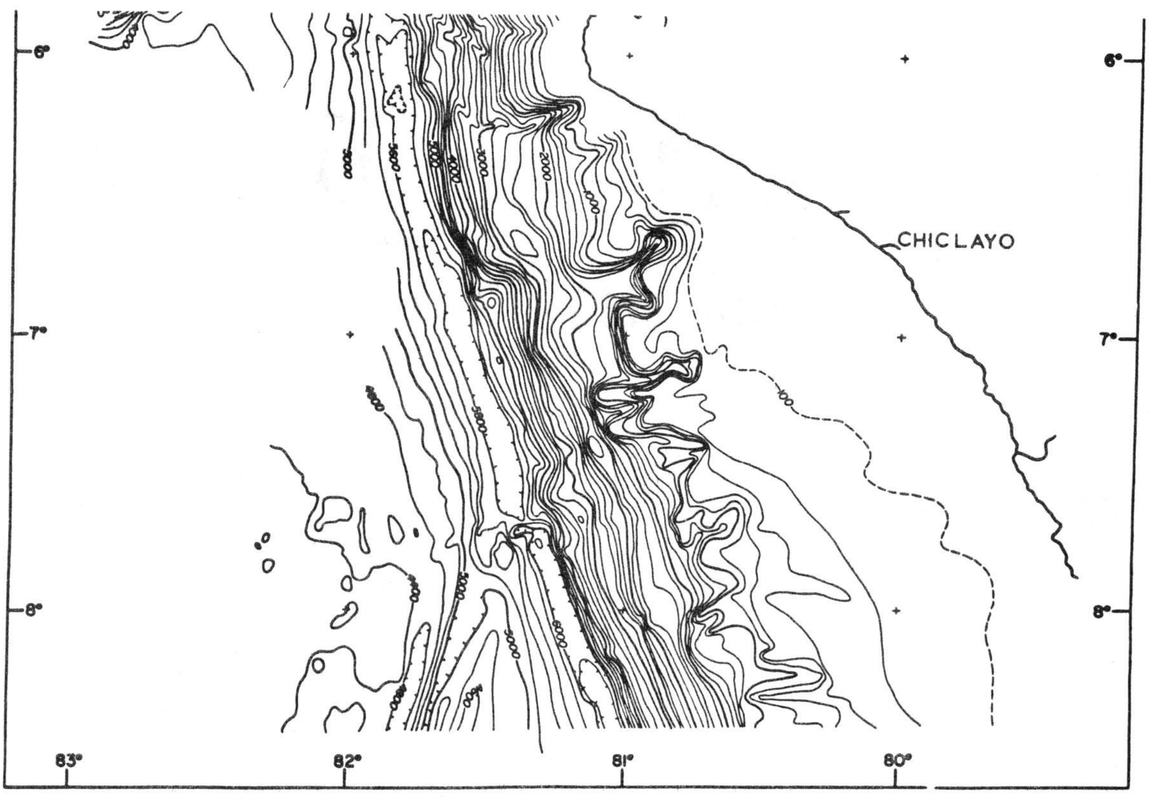


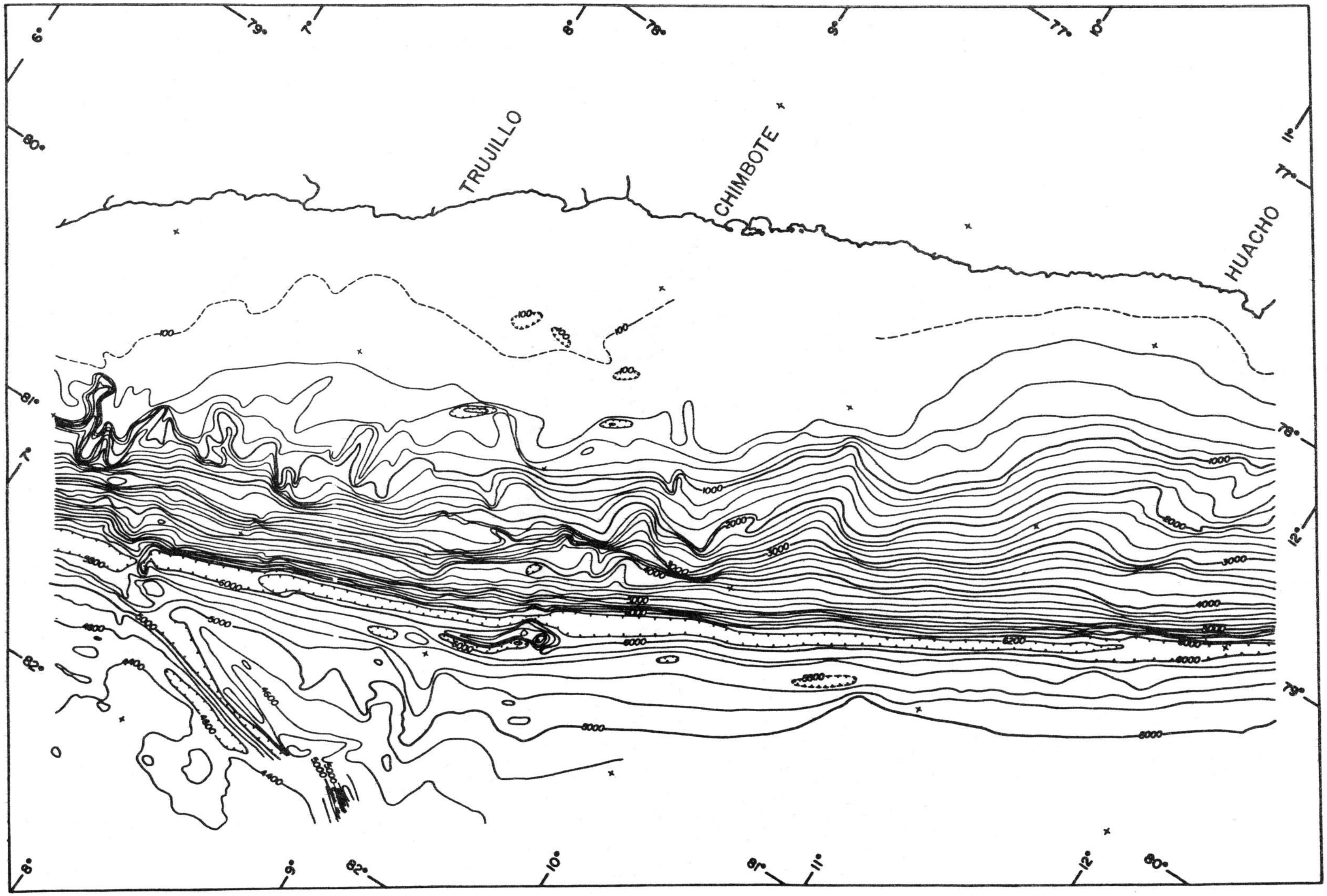
Figure 2. Track line map showing locations of bathymetric and seismic reflection profiles.

Figure 3. BATHYMETRIC MAP

Compiled by: Roger Prince (1974) 6° to 10°S
Antonio Masias (1975) 10° to 13°S
Gordon Ness and R. Prince (1975) 13° to 18°S

Contours in corrected meters.
Oregon State University





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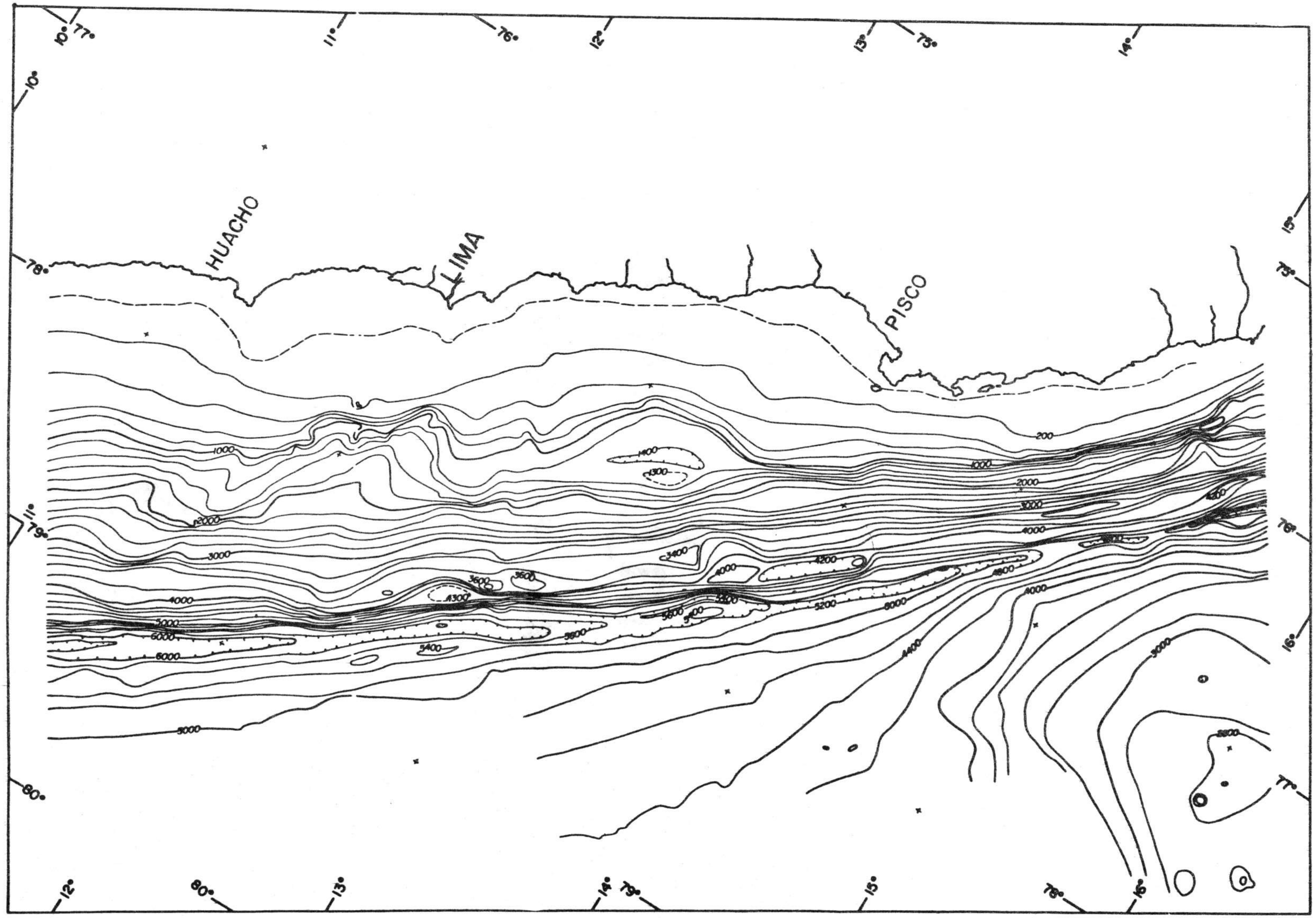

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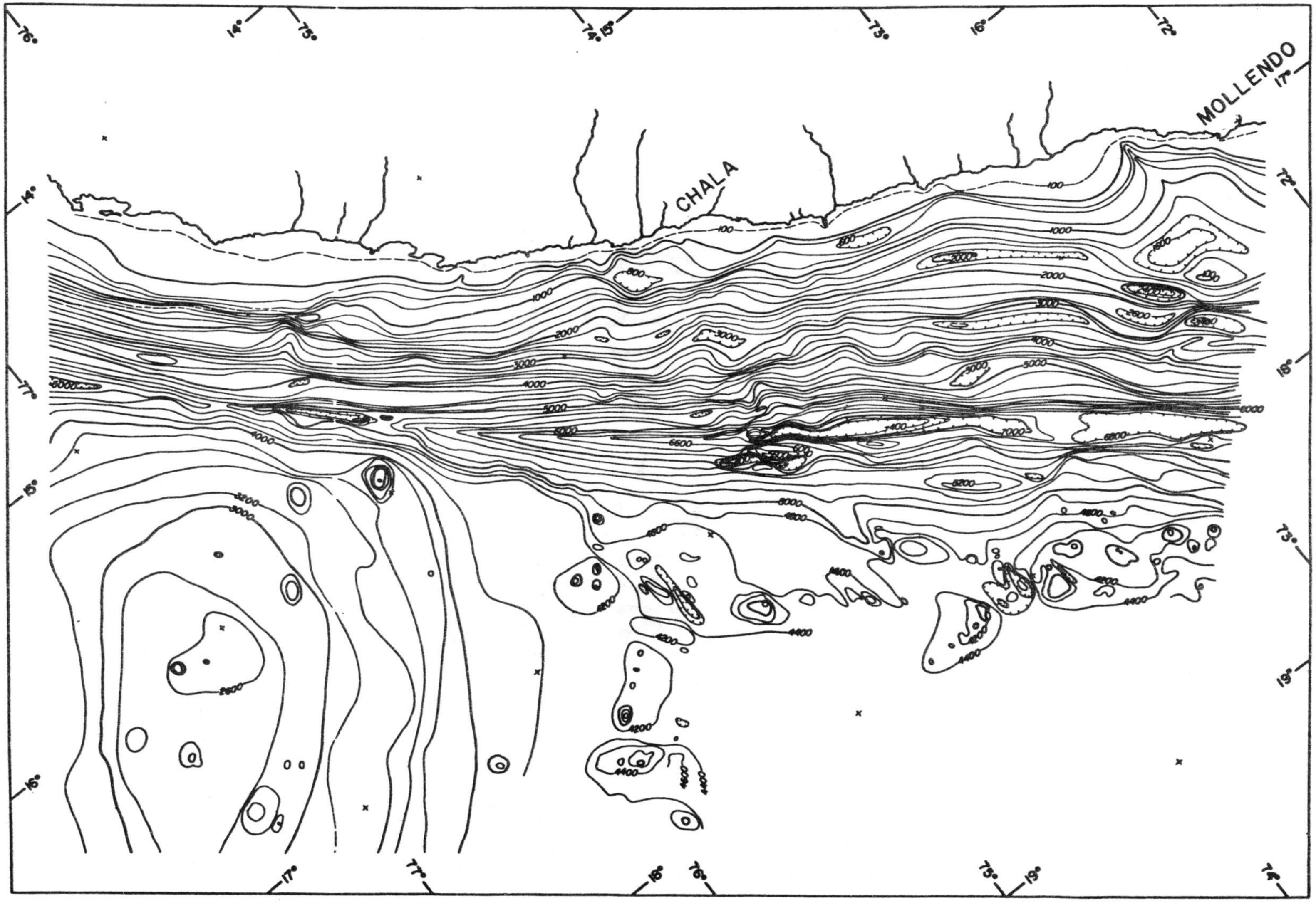

Figure 3. continued

PHYSIOGRAPHIC PROVINCES

The mountains in the Cordillera de Los Andes traverse Peru from southeast to northwest, dividing the country into longitudinal provinces of pronounced geomorphic contrast. These provinces include, from northeast to southwest, the Sub-Andean Region, the Cordillera Region, and the Coastal Region (Fig. 4). Offshore the continental margin consists of the usual continental shelf and continental slope. The slope is divided into four physiographic provinces (A-D). The Peru Trench lies at the base of the continental slope.

Onshore Region

Sub-Andean Region

The Sub-Andean province is characterized by the vast Amazonian Plain and the low mountain ranges of the Sub-Andean system along the eastern side of the Andean Cordillera. The Amazonian Plain is an erosion surface underlain by Tertiary red beds, and it is partially covered by Pliocene to Recent lacustrine and fluviatile deposits.

Andean Cordillera

The Andean Cordillera province extends across Peru in a southeast-northwest direction. According to Bellido (1969), it consists of

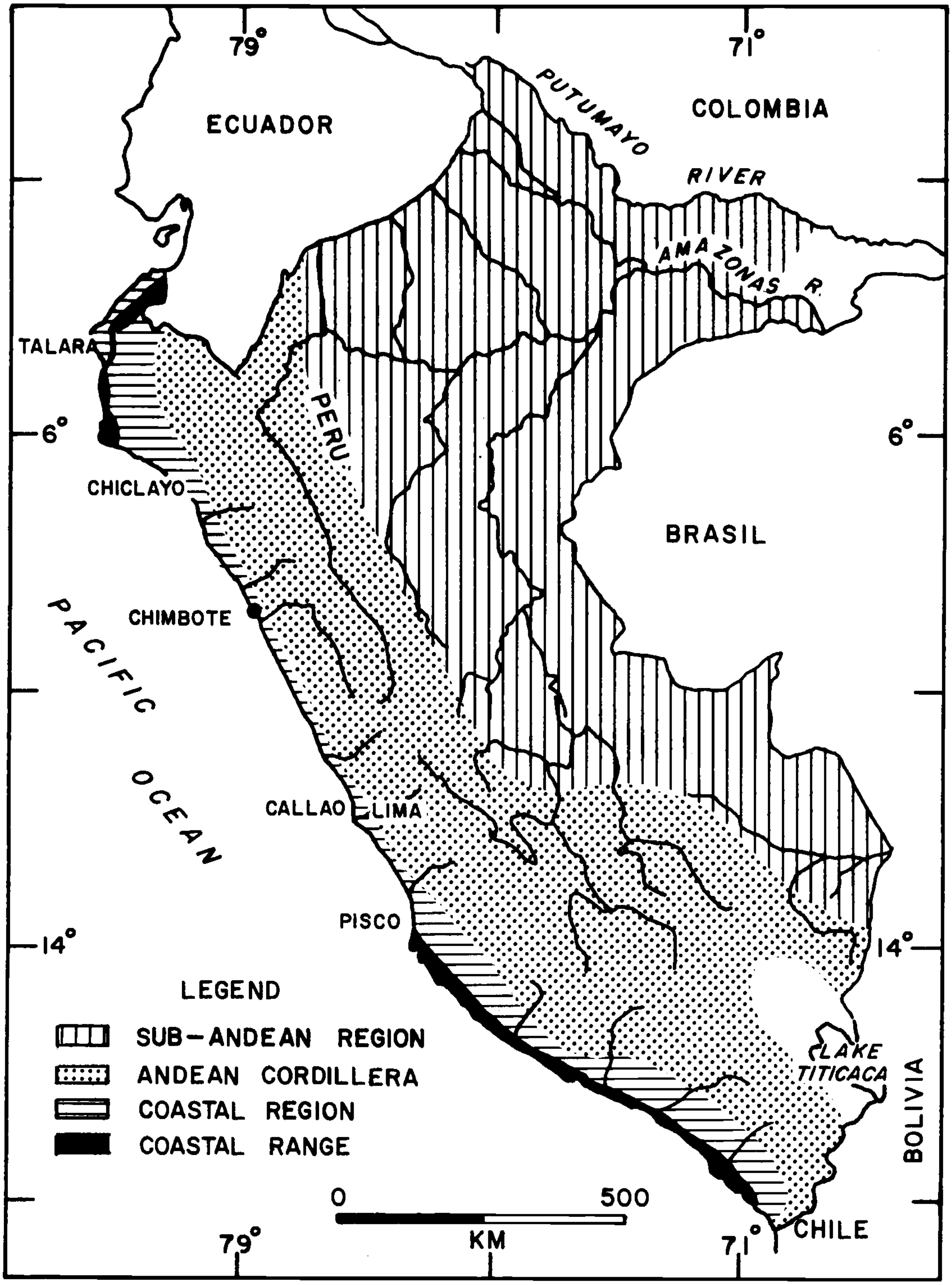

Figure 4. Physiographic provinces along the western part of South America (Peru).

three well defined longitudinally oriented features: 1) the western Cordillera (Cordillera Occidental); 2) the eastern Cordillera (Cordillera Oriental); and 3) the Sub-Andean Cordillera. The Cordillera Occidental is the highest mountainous feature trending parallel to the Pacific coast and forms the Pacific watershed of the Andes. It includes the Cordillera Blanca, which includes the Nevado Huascaran, the highest peak in the Peruvian Andes (6768 m), the Huaywash Cordillera and the southern volcanic region.

Coastal Region

The coastal region forms a narrow belt along the western border of the continent (Fig. 4) and is characterized by coastal plains, low hills and marine terraces. Three major Pleistocene marine terraces (Mancora, Talara and Lobitos) are recognized in the northern area. The terraces are especially well developed in the northern part of the coastal region. To the north, between the Ecuadorian border and Trujillo, a well developed coastal plain reaches a maximum width in the vicinity of the Sechura Desert.

The coastal mountain range appears as a discontinuous chain called the Amotape Mountain and by the Silla de Paita, Cerros de Illescas onshore, and the islands Lobos de Tierra and Lobos de Fuera near the shelf edge off northern Peru.

Farther south, between Trujillo (8°S) and Lima (12°S), the foothills of the Andean belt reach the coast, terminating in cliffed headlands. In this region the coastal plain is characterized by flood-plains and small deltas built by coast rivers. There are no coastal mountain ranges in this region. Small marine terraces, a few meters above the sea level, occur here.

In the southern part of the coastal region, between Cañete and the Chilean border, the coastal range occurs as a discontinuous chain of low hills close to the coast line; the coastal plain is well developed between the coastal range and the foothills of the Andean Cordillera to the west.

Offshore Region

Continental Shelf

The continental shelf extends from the Peruvian coastline to the shelf break which occurs between the 100 m and 200 m isobaths. In general, the continental shelf exhibits a flat almost horizontal surface. Gentle changes in bottom relief are observed locally, close to some of the island chains (discussed previously) that are aligned close to the edge of the continental shelf on the northern shelf (6-7°S) and opposite Lima (12°S). The continental shelf is devoid of sub-marine canyons or submarine banks.

Off northern Peru, the shelf is the narrowest in the vicinity of

6°S (Fig. 5). It widens to an average width of 98 km between 6°40' and 10°30'S. It reaches a maximum width of 126 km (Fig. 5, line 6) off Trujillo and Salaverry. Between 10°30' to 14°40'S the average shelf width decreases to 32 km with the exception of the region near Paracas Bay where it broadens to 80 km (Fig. 5, line 13). South of 14°40'S to the Chilean border the shelf is about 19 km wide. However, the shelf almost disappears in the vicinity of line 23 (Fig. 5) where it is only 5 km wide. Regionally the deepest continental shelf break (about 200 m) occurs between 14° to 16°S.

Continental Slope

The continental slope can be divided into four different provinces distinguished here as A, B, C, and D on the basis of geomorphic characteristics (Fig. 6). Although the boundaries between provinces are not always well defined, the provinces are areas with common physiographic characteristics.

Province A. The northernmost province (A) is located between 6° to 9°30'S (Fig. 6, lines 1 to 6). It has an average width of 90 km and an extremely irregular sea floor. Gradients on the upper continental slope range from 1:45 to 1:35 (Prince, 1974). The middle slope averages 1:16 while the lower slope drops steeply toward the trench with an average gradient of 1:6. This region has several

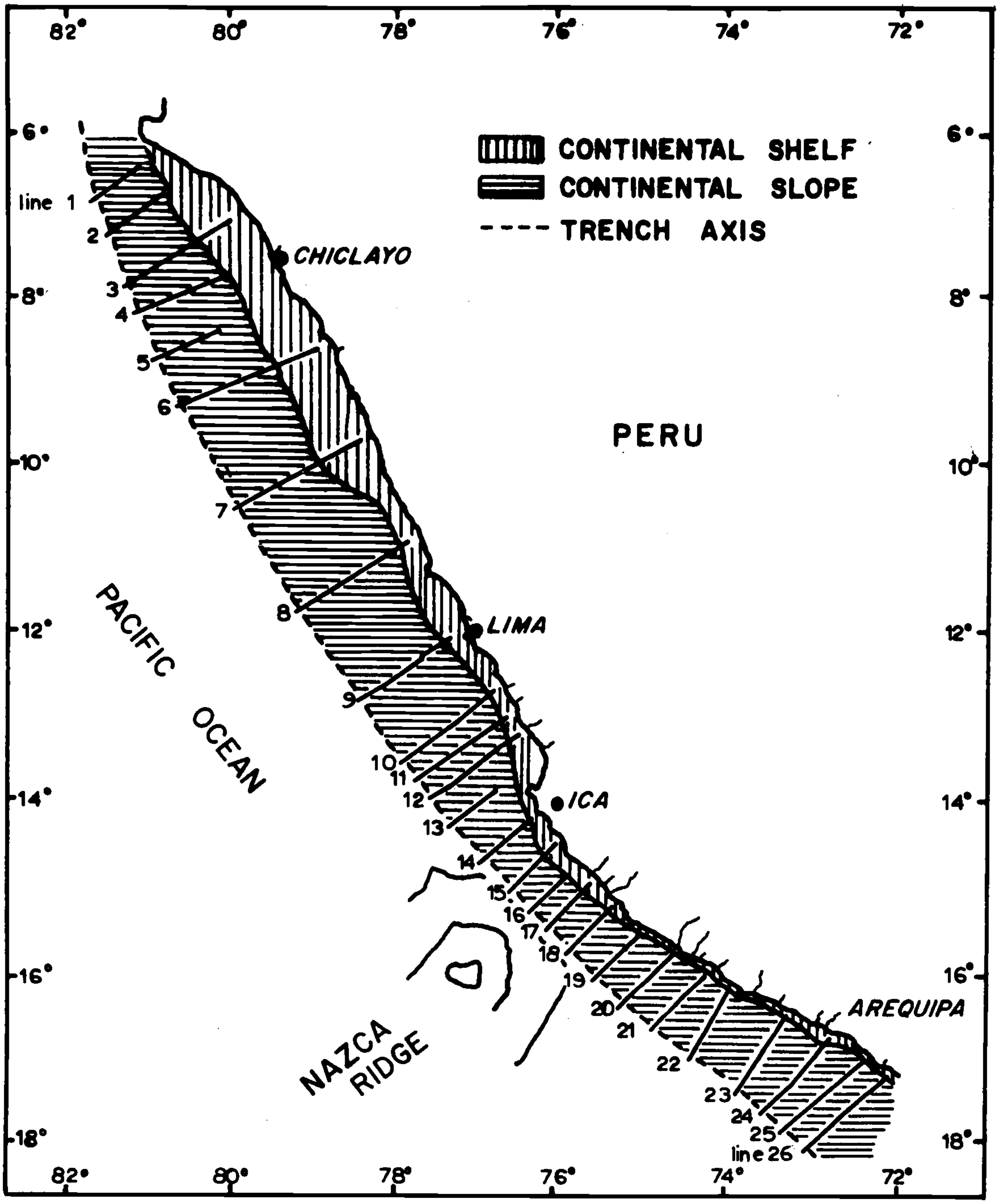

Figure 5. Peruvian continental margin physiographic provinces.

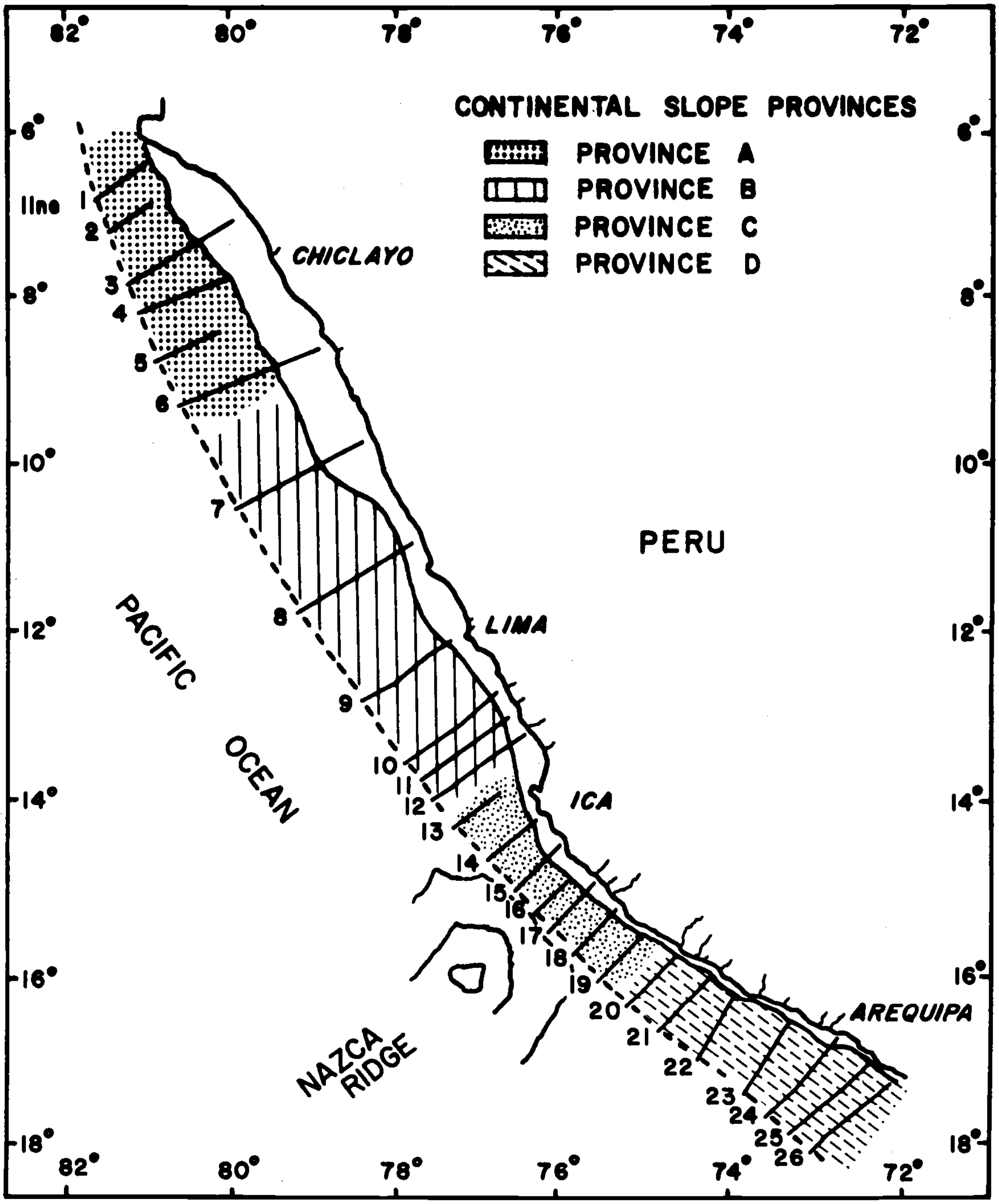

Figure 6. Plan view of continental slope physiographic provinces.

prominent submarine canyons which have their heads near the outer edge of the continental shelf. The most striking and deepest canyon located in the northern part of province A, for example line 2 (Fig. 7), shows a canyon 900 m deep and 14 km wide on the upper slope.

In province A the lower continental slope displays numerous benches. The gradients between benches are generally 1:8 to 1:7, but they may be greater near the trench-slope interface (Prince, 1974). The width of the benches varies from 0.5 to 10 km. A number of benches can be traced parallel to the continental slope for distances up to 60 km. Some benches decline to the north and some to the south.

Province B. This province is located between 9°30' to 13°S (Fig. 6, lines 7 to 12) and is characterized by the absence of large submarine canyons. The most prominent feature in this province is the Lima Plateau. The plateau is located on the upper slope and lies at a water depth of about 1500-2000 m. It is 30 km wide and about 250 km long. The plateau dips westward with gradients up to 1:65. The middle slope has an average gradient of 1:15 while the lower slope drops toward the trench with an average gradient of 1:8.

Benches are less prominent and, in general, the relief of the slope is more gentle than in province A. A prominent bench occurs on the lower slope, from 12°30' to 14°30'S. It is 10 km wide, lies

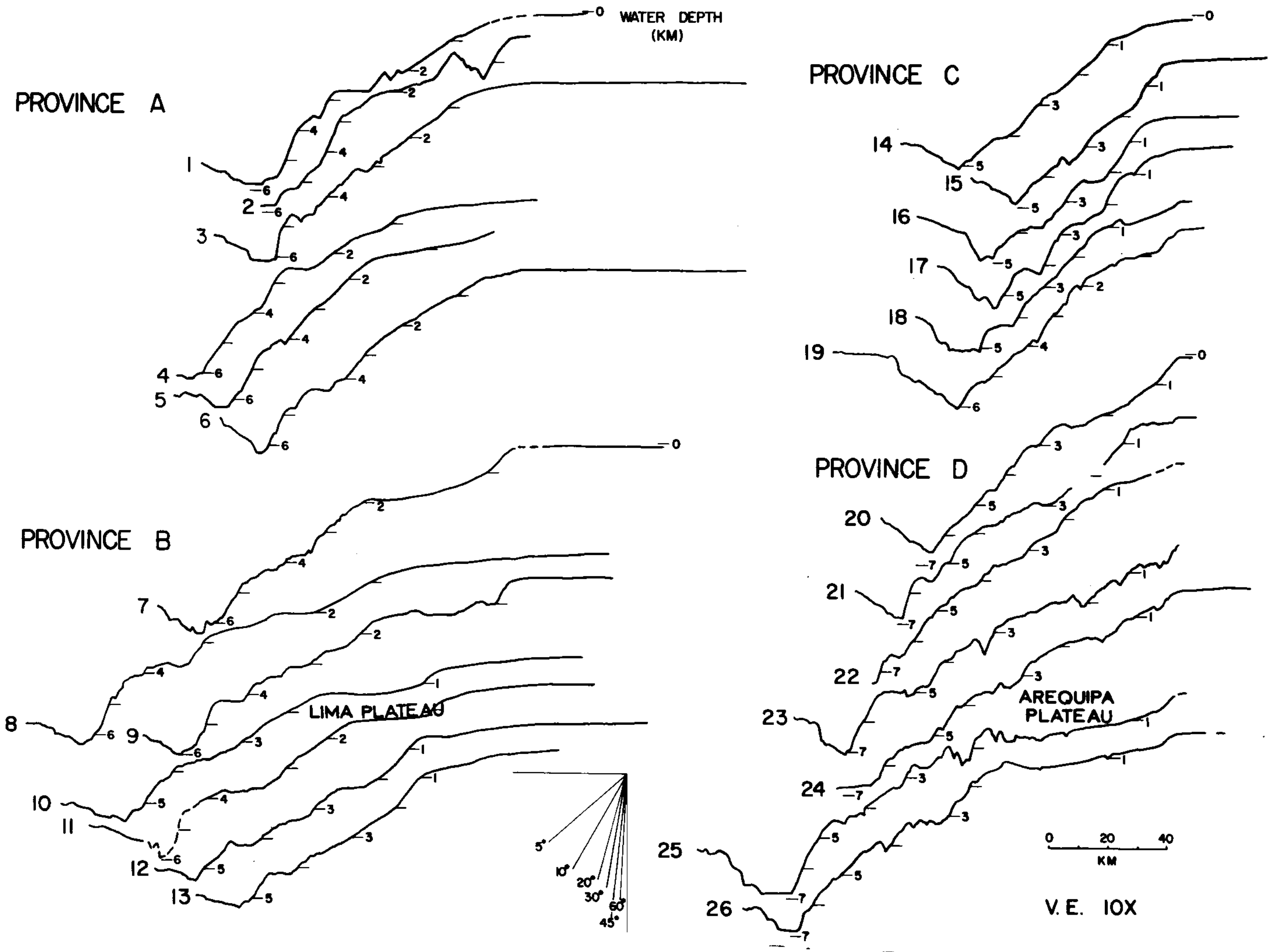

Figure 7. Physiographic provinces and bathymetric profiles. Note locations of Lima and Arequipa Plateaus.

at depths of about 4000 m, and can be followed along the slope for a distance up to 160 km. This feature is characterized by a rather smooth surface.

Province C. This province is situated between 14° to 16°S (Fig. 6, lines 13 to 20) and is associated with the Nazca Ridge. The continental slope is narrow here (average width 68 km) with the narrowest point (54 km) being located along Line 15. The shelf break deepens abruptly in this province and occurs at an average depth of 200 m. The deepest regional shelf break occurs in this province. The shelf break has a rather steep gradient of 1:13. Average gradient for the middle and lower slope are 1:9 and 1:8, respectively. These gradients are steeper than those in provinces A, B, and D.

A bench-like feature, 5 km wide, is present on the middle slope (Fig. 7, line 16) at depths of 2300 m. Another bench-like feature occurs on the lower slope between Lines 15 to 19 (Fig. 7); its surface declines from a depth of 3600 m (line 15) to 5200 m (line 19). This feature is 5 to 10 km wide and can be traced for a distance up to 200 km along the slope.

Province D. In this province the slope averages 104 km in width. The topography shown in lines 20 to 22 (Fig. 6) in province D appears to be a transition between provinces C and D. In this province (16° to 18°S) the upper slope has an average gradient of 1:28, the middle slope 1:12 and the lower continental slope about 1:6 (Fig. 7, lines 20 to 26).

The most prominent feature in this province is the Arequipa Plateau (Fig. 7, lines 25 to 26). This plateau is 500-1300 m deep, about 50 km wide and appears to extend into northern Chile. Canyons are generally small or absent. A canyon 2 km wide and 200 m deep heads at a depth of 1000 m (line 26). It is deeper to the north and can be followed along lines 25 (1500 m), 24 and 23 (Fig. 7) for a distance up to 150 km.

The middle continental slope (Fig. 7, lines 23 to 26) depicts an irregular topography, several submarine canyons, benches and an apparent plateau whose continuity is difficult to follow. These features cannot be correlated along the slope because of the abrupt lateral topographic changes between lines.

In province D the topography of the lower continental slope seems to be more uniform and a large bench declines toward the trench with a gradient of 1.6.

Trench

A striking depression, the Peru Trench, lies at the juncture of the South American Block and Nazca Plate. It is an arcuate, concave outward feature which extends along the continental margin. It shoals gradually from depths of 7415 m in the south to 5780 m in the north.

Based upon regional changes in depth of the floor, the trench can be divided into three provinces (Fig. 8). The northern province between 6° to 11°45'S (Fig. 8, lines 1 to 8) shows an average depth of 6126 m with the deepest part occurring at 6329 m on Line 8. The axis is 8-14 km wide and displays an almost flat floor between 6° to 8°S (Prince, 1974). In this northern province three prominent ridges have been recognized in the trench axis (Kulm et al., 1973; Prince, 1974; Prince and Kulm, 1975).

The central province, between 11°45' to 17°S (Fig. 8; lines 9 to 22), is associated with the Nazca Ridge, and the trench has an average depth of 5760 m, but rises to its shallowest depth of 4877 m in the vicinity of the Nazca Ridge. In this province the trench floor is characterized by a narrow depression.

A striking change in depth marks the boundary between the central and southern provinces. The southern province is located between 17° and 18°S (Fig. 8; lines 23 to 26). The trench floor has an average depth of 6927 m; it varies in width between 7 km (line 24) to 4 km (line 26) and has a flat almost horizontal floor.

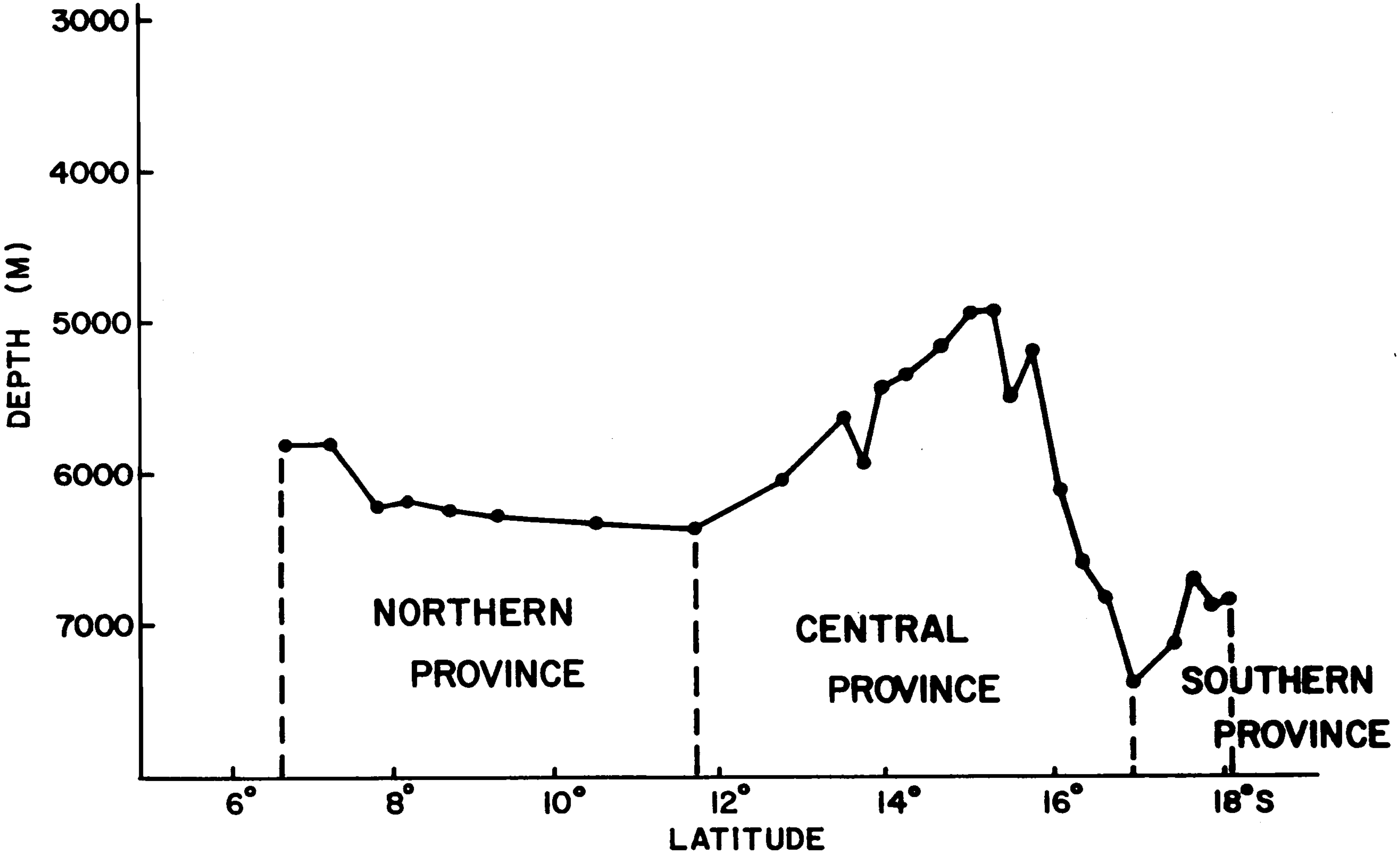

Figure 8. Peru Trench provinces.

GEOLOGIC SETTING

The geology of Peru has been difficult to interpret for many years. Von Humbolt and a group of European scientists conducted investigations in 1802 that covered the northern part of the country. In 1850 the geographer Antonio Raimondi initiated the systematic exploration of the country and since that time, with the exception of periods of limited activity, an impressive body of information was obtained by many scientists which contributed to the knowledge of the geology of Peru.

According to the plate tectonic hypothesis, the Andean Cordillera is an example of a developing fold belt at the edge of a continental plate through the processes of subduction. However, the geology and processes taking place within the continental margin are still poorly understood. In an attempt to better understand the geologic processes that are taking place on the continental margin, a brief description of the coastal region geology is presented. The onshore geology will be extrapolated to the adjacent continental shelf and upper continental slope. Data for the middle and lower continental slope and trench are available from previous studies of the area.

Onshore Geology

Pre-Mesozoic rocks are exposed in the coastal ranges of southern and northwestern Peru (Fig. 9). These older rocks have been inferred on the basis of their position locally beneath fossiliferous strata of early Paleozoic age or on the basis of regional metamorphism. Recent radiometric age determinations (K-Ar and Rb-Sr) have confirmed the Precambrian ages of these strata (Stewart et al., 1974). Ages of 679 ± 12 m.y. and 642 ± 16 m.y. old have been documented along the trend of the Arequipa batholith in southern Peru (Stewart et al., 1974) (Fig. 9). Pre-Mesozoic rocks also occur in the Silla de Paita and Cerro de Illescas of northwest Peru where they are comprised of granite, gneiss, and chlorite and mica schists (Steinmann, 1930).

In the coastal range of southern Peru the Mollendo gneiss consists of quartz-feldspar-biotite gneiss probably formed by regional metamorphism (Jenks, 1948). These rocks have been correlated with the strata on the Paracas Peninsula (southern Peru) which are composed chiefly of red granite and porphyritic rhyolite or gneiss and greenish gray amphibolite (Sanz, 1974).

Precambrian igneous rocks, chiefly granodioritic to granitic in character, have a high alkali content (Steinmann, 1930) and are present in the coast range in southern Peru. No known rocks of Cambrian, Ordovician and Silurian age have been reported along the Peruvian coast. Devonian rocks with a collective thickness of about 6000 m occur in the Cerros Amotape and the Silla de Paita in

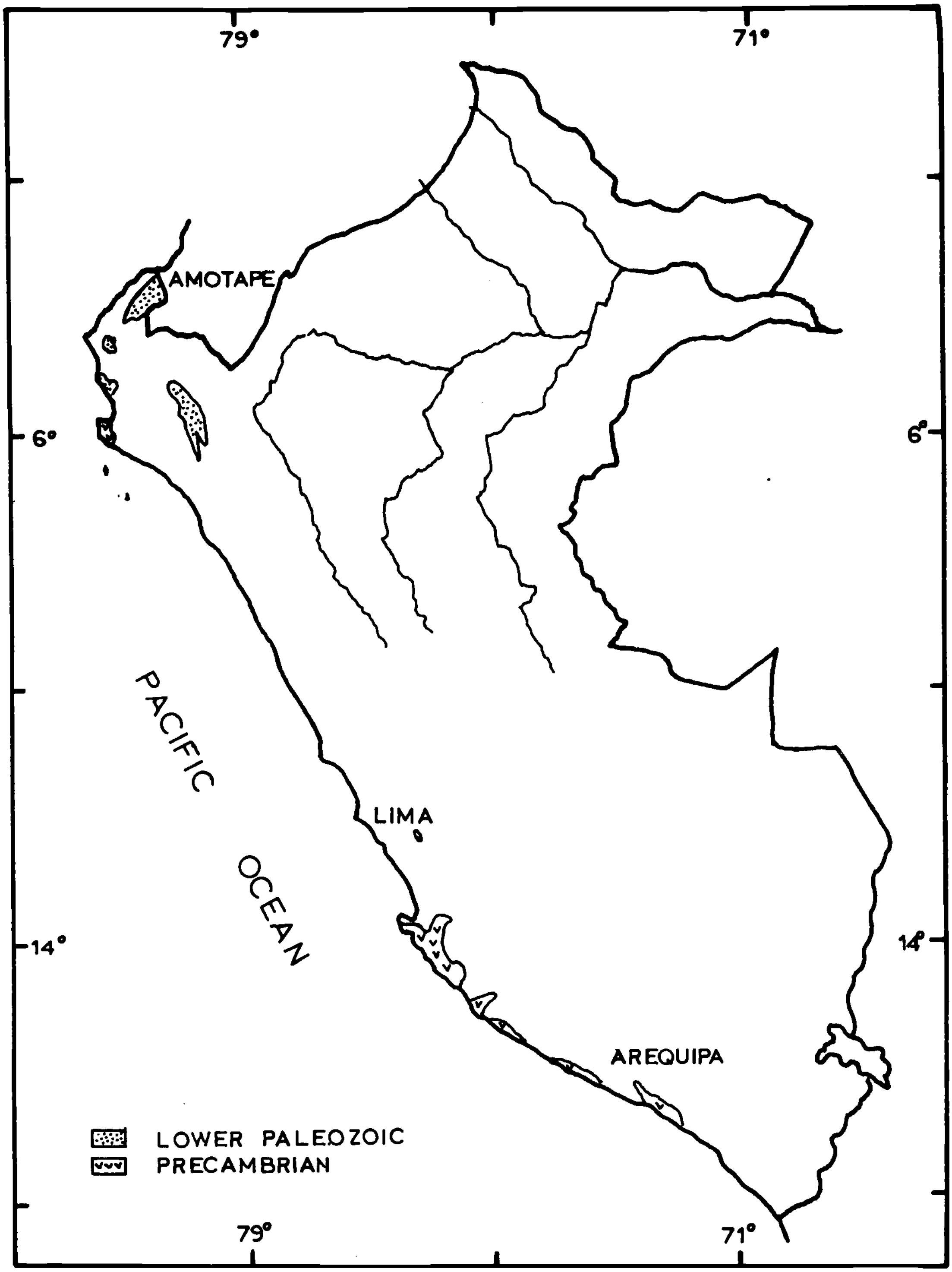

Figure 9. Distribution of Pre-Mesozoic rocks in the Coastal Ranges of Peru.

northwest Peru (Petersen, 1949); this section is comprised of dark shales, siltstones, sandstones, and graywackes which are slightly metamorphosed to phyllite and quartzite.

Mississipian rocks along the Peruvian coast are characterized by the Ambo Group which is present in the Cerros Amotape and the Silla de Paita of northwest Peru (Chalco, 1954). They generally consist of continental sandstone, shale, graywacke and local conglomerate.

Pennsylvanian rocks are marine in character and have been reported in the Amotape Formation of northwest Peru and in the coastal region of the Arequipa Department (Newel et al., 1953). They are dominated by quartzose sandstones with interbedded shales. A series of limestones and shales overlie these lithologies with slight angular unconformity. Pennsylvania beds have been described by Fernandez-Concha (1950) and Rueg (1957) on Marcona at about 15°S.

Paleozoic intrusive rocks of probable Permian age have been reported in the southern Peruvian coast and northwest mountain ranges (Fernandez-Concha, 1950; Rueg, 1957). Hosmer (1959) pointed out that these intrusives belong to the calc-alkalic suite and commonly have undergone later deformation.

Mesozoic sedimentary and volcanic rocks are distributed widely along the coast. Volcanics of Mesozoic age include submarine pillow lavas, tuffs and agglomerates. They are identified mainly as andesites and basalts corresponding to the Late Triassic to Early and Late Jurassic units. These lithologies also have been identified in the Arequipa region, Ica Department and northwest Peru. The early Mesozoic volcanics are more than 2300 m thick as suggested by the incomplete stratigraphic sections located northeast of Chiclayo (Fisher, 1956) and reach to elevations of 4000 m at Chala in the coastal region of Arequipa (Hosmer, 1959).

Late Triassic and Early Jurassic rocks in northern Peru consist of andesitic flows with marine sandstones, shales and mudstone of a dark gray color called the Zaña Group (Bellido, 1969). Along the southern coast (the Departments of Arequipa, Moquegua, and Tacna) (Fig. 10) the Late Triassic and Early Jurassic units are represented by the Yamayo Group and the Chocolate Volcanic Group (Jenks, 1948).

After an interval of volcanic quiescence in the middle Late Jurassic (Hosmer, 1959), renewed vulcanism produced the Puente Piedra volcanics of the Late Jurassic and Early Cretaceous age in the central coastal region near Ica and Lima. These lithologies consist mainly of andesitic flows, tuffs and agglomerates with some interbedded shales, siliceous limestones, sandstones, graywackes and conglomerates (Rivera, 1951). Late Jurassic rocks are represented by the Chicama Formation which consists of a marine sequence of gray light to gray dark shales, sandstone and clay.

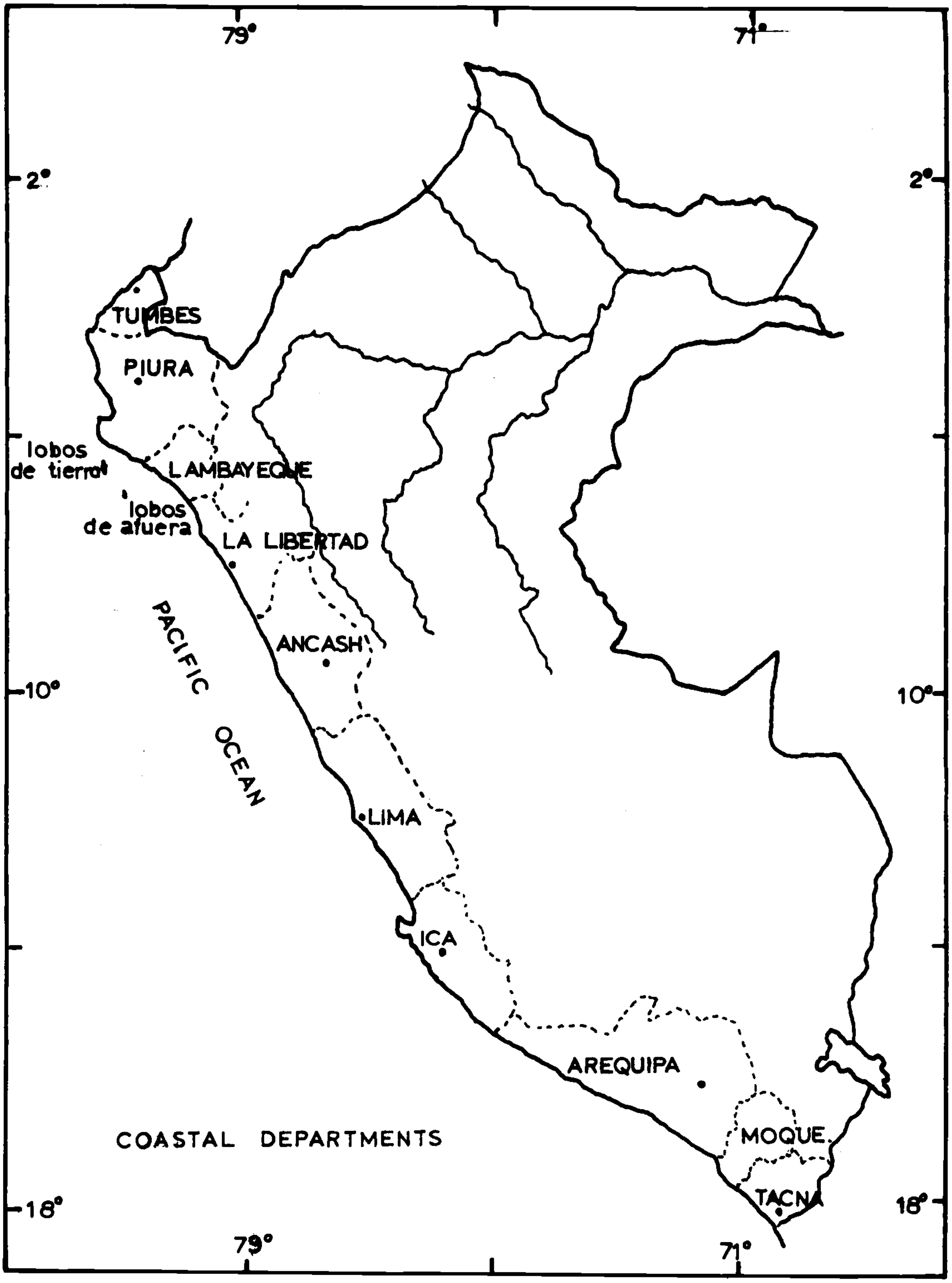

Figure 10. Coastal Departments of Peru.

This sequence is present at Chicama Port between Trujillo and Chiclayo (Bellido, 1969).

Cretaceous geosynclinal deposits crop out extensively in the western Cordillera. Volcanic facies occur locally along the coastal region and Cretaceous vulcanism preceded the intrusion of the Andean batholith in the Cordillera Occidental and southern Peru (Hosmer, 1959). Cretaceous rocks are found in the Tumbes and Piura Departments in northwest Peru, Nazca and Pisco in the Ica Department of central Peru, and near Camana in the southern part of the country. Between 8°S to 11°30'S, along the coast, middle Late Cretaceous rocks are characterized by the Casma Formation that consists of sandstones, shales, graywackes, interbedded with some andesitic flows. In northwest Peru, Late Cretaceous to early Tertiary fossiliferous marine deposits are present and have been studied by Iddings and Olsson (1928), Travis (1953) and others. The Late Cretaceous rocks are represented by the Redondo, Petacas and Mal Paso Groups. Their lithologies varies from a pebble conglomerate to dense micaceous shale, fine quartz conglomerate and coarse-grained sandstones. Volcanic rocks of the Calipuy Formation of Late Cretaceous to early Tertiary age are exposed widely along the coast of La Liberated and Lima Departments (Fig. 10).

Tertiary lithologies along the Peruvian coast are characterized by both marine and continental sediment. Marine sedimentary rocks occur along the coast of Tumbes, Piura, Lima, Ica and Arequipa Departments (Fig. 10). They consist mainly of shale, sandstone, and conglomerate that were deposited in shallow seas (Bellido, 1969).

Plutonic rocks, which form the Andean batholith, are present along the southern coast and western Cordillera. These rocks belong to the calc-alkalic suite (Hosmer, 1959). Granodiorite is the main constituent and tonalite, diorite and quartz monzonite are abundant; gabbro, syenite and granite are present in lesser amounts. A series of late porphyritic intrusives occurs in the batholithic belt in southern Peru. These intrusions include quartz monzonite porphyry, dacite porphyry, fine grain granite and latite porphyry (Jenks, 1948).

Quaternary and late Tertiary deposits of marine and continental origin cover extensive areas along the coast. Lithologically they are characterized by clays, calcarenites, conglomerates and shales. Along the northern part of the Peruvian coast Quaternary marine deposits form extensive marine terraces. Less extensive small terrace deposits are present along the southern Peruvian coast.

Offshore Geology

The geology of the Peruvian continental shelf south of 6° is poorly understood. The lack of sample information or published drill hole information makes it difficult to extrapolate the onshore geology to the offshore region. Despite these obstacles, the onshore geology is extrapolated into the offshore region on the basis of the following information: 1) location and orientation of coastal sedimentary basins; 2) trends of gravity anomalies from coastal basins seaward onto the shelf (Whitsett, 1975); 3) seismic reflection profiles from the present study; and 4) unpublished drill hole data of two wells located near the edge of the continental shelf in front of the Salaverry Basin (9°S). Based on the onshore geology discussed previously, it is believed that the Precambrian rocks found in the coastal region of northern and southern Peru presently form the core of the outer continental shelf high (acoustic basement) off central Peru and the core of some islands aligned close to the edge of the continental shelf off northern Peru (Fig. 10).

In southern Peru Precambrian rocks occur in the core of the Coastal Ranges and this core may in part form the basement of the sedimentary basins on the upper slope which also display an acoustic basement. Precambrian rocks apparently also form the basement of the continental shelf basins off northern Peru. Paleozoic strata might overlie older Precambrian rocks in the outer continental shelf high and partially form the basement of the Sechura, Salaverry and Pisco Basins on the continental shelf. Paleozoic rocks crop out on the offshore islands of Lobos de Tierra and Lobos de Afuera Islands in northern Peru (Fig. 10), and have been reported at comparatively shallow depths in an offshore drilling program in the outer shelf high near 9°S (Cobbing and Pitcher, 1972). Although the drilling results were announced in the newspaper in Lima, Peru, they have not been published in any other form. The lithologies of the basement rocks are believed to be quartz biotite gneiss and dark gray phyllite.

Mesozoic sedimentary and volcanic rocks cover extensive areas along the Peruvian coast and are believed to extend onto the continental shelf (Zuñiga and Travis, 1975). Sedimentary rocks of this age may overlie Paleozoic strata in northern and central Peru. In southern Peru Mesozoic strata are unknown and might be absent offshore.

Late Cretaceous and Tertiary marine deposits are largely confined to a narrow coastal belt onshore, and their presence is assumed offshore. Although marine deposits in northwestern Peru have been dated extensively by fossils, the broader limits of these deposits elsewhere in the coastal region have been established on the basis of scattered fossil correlations. All of these strata are probably present offshore and form the bulk of the sedimentary sequence in the Sechura, Salaverry and Pisco Basins in the continental shelf.

Middle and late Cenozoic sediments may overlie older rocks on the seaward side of the outer continental shelf high (i.e.: the Lima Basin on the upper continental slope). These sedimentary deposits are about 2 km thick (Kulm et al., 1975) and were deposited over the Peruvian continental margin, in part, during the various sea level lowerings associated with Pleistocene glaciation and previous events. Rosato (1974) studied about 100 piston core samples randomly distributed on the continental shelf, continental slope and trench and pointed out that only one sample was older than Quaternary and it was taken on the Nazca Plate. Although the length of the piston cores was up to 16 m, none of the subsurface samples were older than 2 m.y.

DISTRIBUTION OF SEDIMENTARY BASINS

Sedimentary basins along the Peruvian coast are known from onshore geology and their offshore extensions which are projected on the basis of regional trends (Fig. 11). The Progreso and Talara Basins are located north of 6°S and are not discussed in the present work. The Sechura, Salaverry and Pisco Basins are well known from onshore geology and their extensions are traced offshore using seismic reflection profiles.

Prominent basins also occur on the upper continental slope and will be discussed in this study. They have been named with respect to their geographic position relative to Lima and Arequipa. The upper continental slope basins are generally longer than basins on the continental shelf. For example, the Lima Basin extends from 9°S to 14°S and the Arequipa Basin from 16° to 20°S. The Salaverry Basin, which is situated on the continental shelf, has the thickest sedimentary deposits and, in general, basins on the continental shelf have a thicker sedimentary sequence than basins on the upper continental slope.

Sechura Basin

The Sechura Basin is located between the structural highs of Paita, Sullana and Lambayeque (Fig. 11). The eastern boundary is

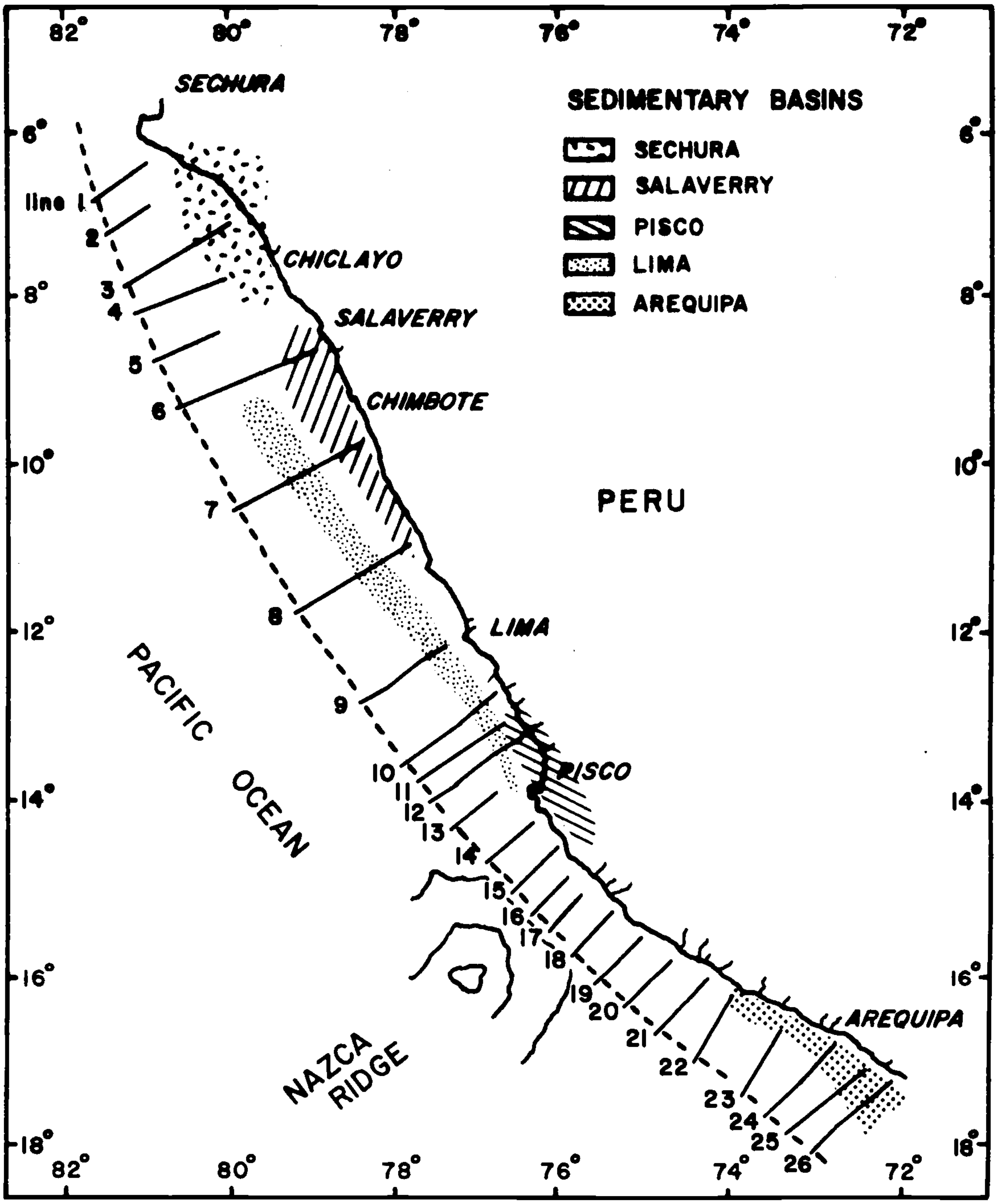

Figure 11. Distribution of sedimentary basins on the Peruvian continental margin, 6°-18°S. The Lima and Arequipa Basins are located on the upper continental slope, the other basins on the shelf.

marked by the lowlands of the Cordillera Occidental, while the western boundary is marked by the Cerro de Illescas high onshore and the offshore islands of Lobos de Tierra and Lobos de Afuera. This basin is about 270 km long and about 110 km wide. The axis of the basin has a north-south orientation. Approximately one-third of the basin is located on the continental shelf and the remainder is located onshore. Sediment thicknesses in this basin range up to 6000 m based on drill holes and onshore geology (Zuñiga and Travis, 1975). Basin deposits are believed to consist mainly of early and late Tertiary terrigenous and volcanic sediments (Pardo, 1973).

Salaverry Basin

The Salaverry Basin is situated mainly on the continental shelf in front of the Lambayeque and Lima Departments (Fig. 11). The western boundary is marked by the prominent basement high which occurs beneath the outer continental shelf (Fig. 12). This high is believed to be Paleozoic strata which form a continuous arc linking the Paleozoic strata of the Amotape Mountains of northwestern Peru with the Paleozoic strata of the coastal range (Cadena Costanera) of southern Peru (Kulm et al., 1973). Older Precambrian rocks crop out in these mountainous areas and may form the core of the basement high beneath the continental shelf off central Peru. The Salaverry Basin has an elongate shape being wider toward the north

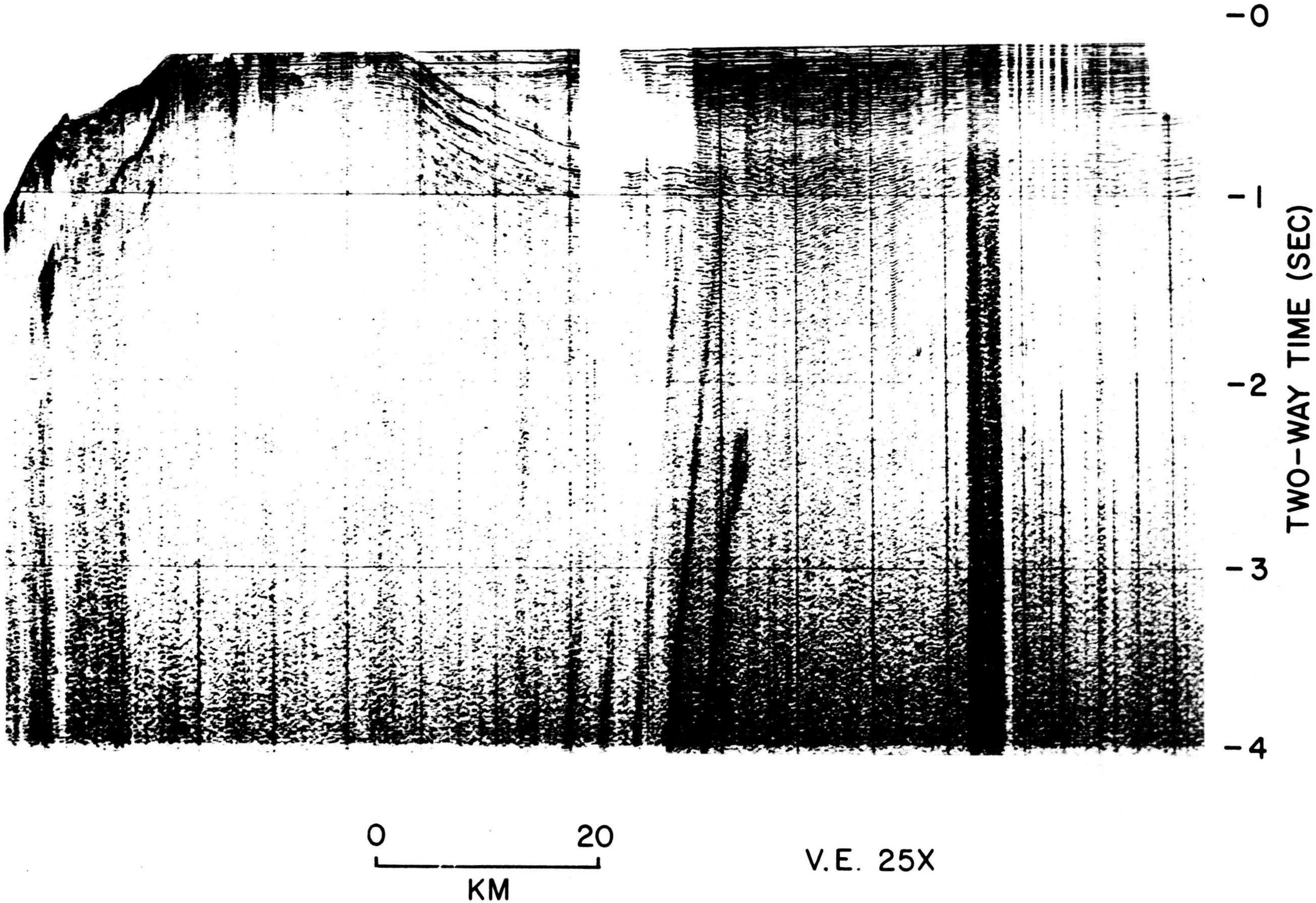

Figure 12. Seismic reflection profile 6. See Figure 11 for location.

and narrower toward the south. It is approximately 500 km long, being 150 km wide in the vicinity of Salaverry and about 100 km wide in the vicinity of Huarmey. The basin strikes in a northwest-southeast direction parallel to the coastline.

Onshore geology suggests that the sediments in this basin are marine Tertiary deposits overlying probable early Cretaceous sediment; they reach a cumulative thickness of about 3000. Eastward (landward) migration of the depositional centers can be seen in some of the seismic reflection profiles made across the basin (Fig. 13). This suggests uplift of the seaward edge of the basin as will be discussed later (see section Basin Migration, p. 50).

Pisco Basin

The Pisco Basin is located along the shore off the Ica and Lima Departments (Fig. 11), between the lowlands of the Cordillera Occidental to the east and the outer continental shelf high to the west. A positive free-air gravity anomaly (20 mgals) is associated with this high (Couch and Whitsett, 1975) which suggests a high density mass in the subsurface. The outer shelf high may be a seaward extension of the Paracas Peninsula that is linked with the Coastal Ranges. Its southern boundary is located south of Ica.

The Pisco Basin strikes in a northwest-southeast direction. It is elongate and narrow being approximately 250 km long and 30 km

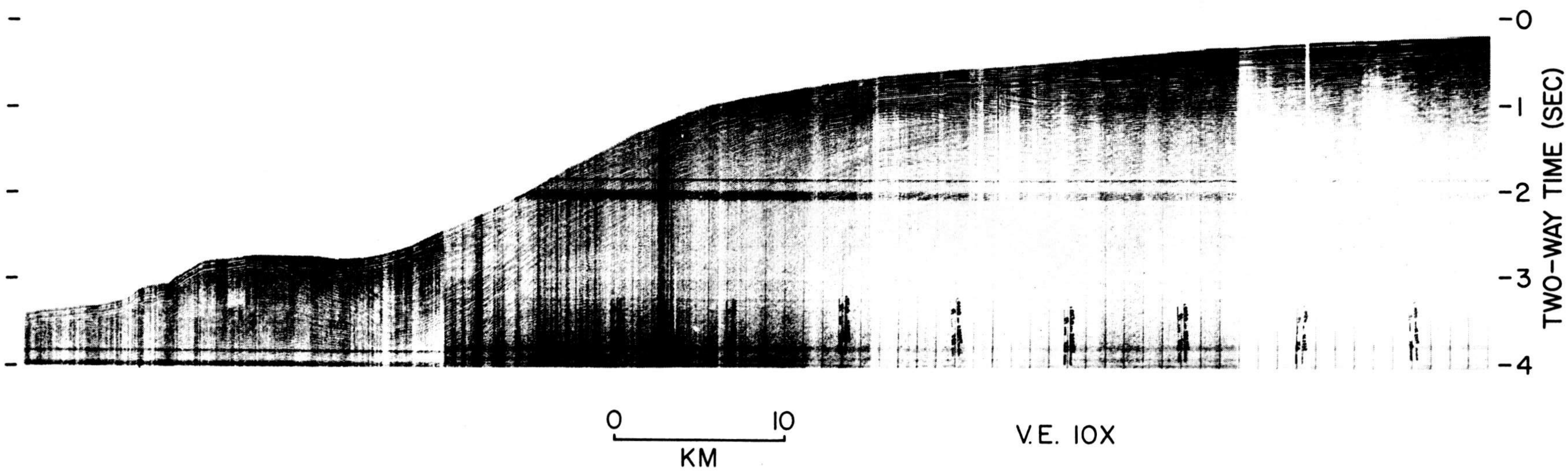

Figure 13. Seismic reflection profile 8. See Figure 11 for location.

wide, respectively. Negative free-air gravity anomalies of 40 and 60 mgals mark the seaward extension of this basin onto the shelf (Couch and Whitsett, 1975). In this basin about 2 km of sediment overlies an apparent acoustic basement. Wide angle reflection measurements indicate a 2.0 km/sec velocity for the overlying sediment with a marked increase to 3.5 km/sec for the apparent acoustic basement (Johnson et al., 1975). Late and early Tertiary strata are present onshore (Petersen, 1954; Bellido, 1969; Sanz, 1973) and are believed to be present in the offshore part of the basin.

Lima Basin

This basin is located on the upper continental slope between 9° to 14°S (Fig. 11). The Lima Basin is much longer than the basins on the adjacent continental shelf. It is about 600 km long and about 45 km wide. The western boundary is the structural high on the middle continental slope. The eastern boundary is the outer continental shelf high which is close to the outer continental shelf break. The northern boundary is not well defined, but seems to be located between lines 6 and 7 (Fig. 11). The southern boundary has been picked between lines 13 and 14 at 14°S.

A 24-fold seismic reflection profile crosses this basin between lines 6 and 7 (9°S) and shows a sedimentary sequence up to 2000 m thick (Kulm et al., 1975). Johnson et al. (1975) describes the southern (13°12'S) part of this basin which has a minimum of 1 km of sediment. Vertical and wide angle reflection profiles made by Johnson et al. (1975) in this area show velocities of 2.0 km/sec for the sediments overlying an apparent acoustic basement with velocities of 3.5 km/sec for the basement deposits. Deposits above the acoustic basement probably consists of middle and late Cenozoic sediments overlying older accreted Nazca Plate and trench deposits within the basement (Kulm et al., 1975).

Eastward migration of the depositional centers in the northern part of the basin (Figs. 13 and 14; lines 7 and 8) and westward migration in the southern part (Fig. 15; line 10) can be seen in the seismic reflection profiles. The tectonic implications of these migrations will be discussed later.

Arequipa Basin

There are no basins on the narrow continental shelf off southern Peru. However, seismic reflection lines 25 and 26 show a fairly large basin located on the upper continental slope (Fig. 11) between 16° to 20°S. The Arequipa Basin is about 45 km wide and may be larger than the Lima Basin to the north. The eastern boundary is the continental shelf break, and the western boundary is the structural high on the middle continental slope. The northern boundary is a narrow extension of this basin toward the north which can be

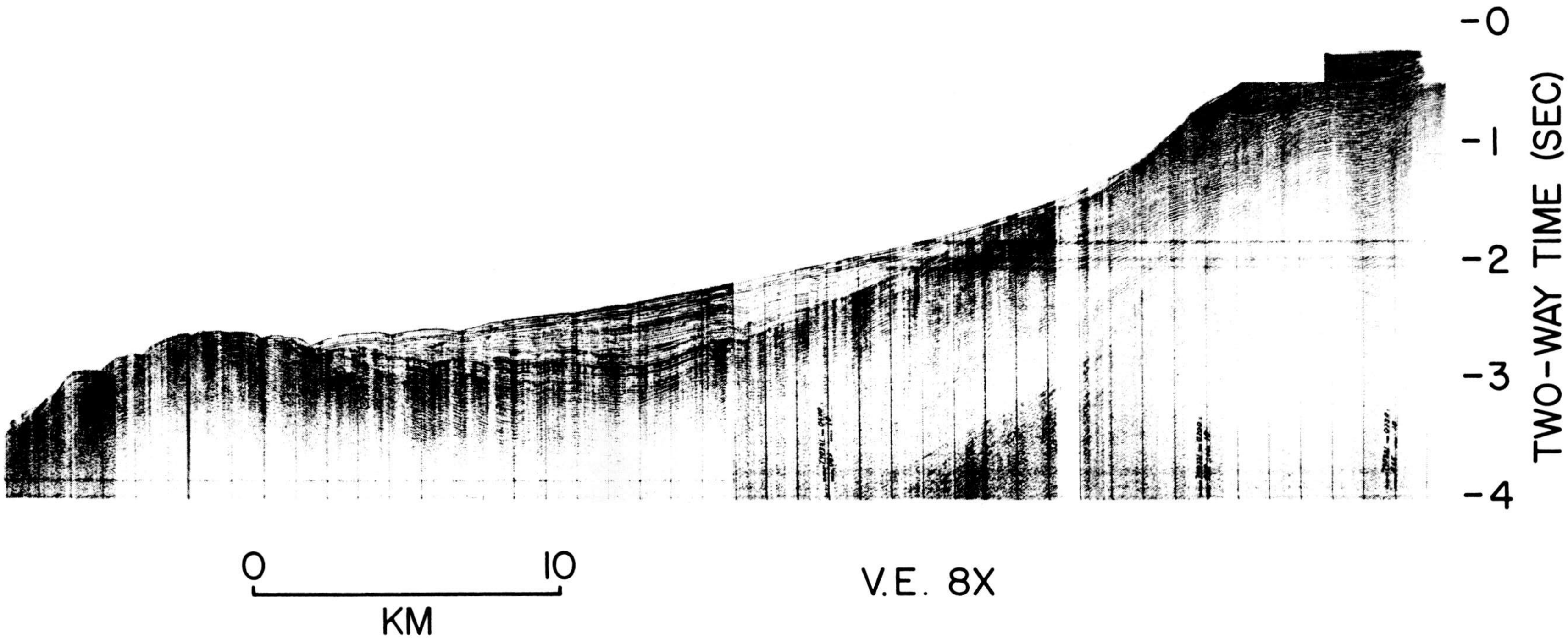

Figure 14. Seismic reflection profile 7. See Figure 11 for location.

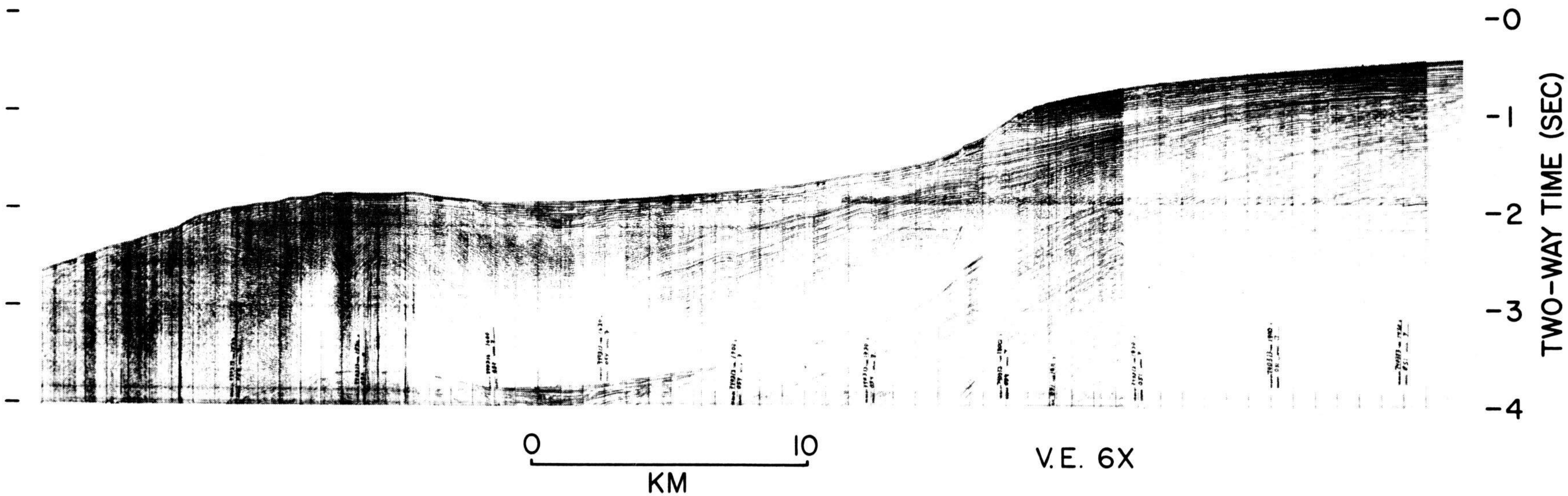

Figure 15. Seismic reflection profile 10. See Figure 11 for location.

followed as far north as 16°S. The southern boundary apparently is located in the northern part of Chile between Antofagasta and Iquique where Coulbourn and Moberly (1975) described an upper slope basin having a maximum sediment thickness of 1.5 sec (two-way time) or 1.5 km at 2.0 km/sec.

Sedimentary sequences range from 1.2 to 1.5 sec thick and are probably late Cenozoic sediment overlying older strata of probable Mesozoic age. This is suggested by the onshore geology which shows middle Tertiary sediment (Camana Fm.) resting upon a well defined marine erosional surface cut into rocks of the pre-Mesozoic complex and the Mesozoic volcanic complex (Hosmer, 1959).

Eastward migration of the depositional centers can be seen in lines 25 and 26. In the southern part of Arequipa Basin, Coulbourn and Moberly (1975) pointed out that the convergence (migration) of unconformities toward the west with time are evidence for uplift along the seaward edge of the basin.

TECTONIC SETTING OF THE PERUVIAN CONTINENTAL MARGIN

General Information

According to the plate tectonic theory, the Peru-Chile Trench is the consequence of the collision of the oceanic Nazca Plate and the South American continental plate (James, 1971; Hayes, 1974). Spreading rates on the East Pacific Rise are the highest in the world. Half rates of 8.2 cm/yr (6°S) and 8.3 cm/yr (11°S) have been reported by Rea et al. (1973). The South Atlantic is opening at a half rate of about 2 cm/yr (Maxwell and others, 1970). Using these spreading rates and poles of rotation, Minster et al. (1974) calculate a convergence rate of 10 cm/yr along the Peru-Chile Trench. Large scale subduction and/or accretion of oceanic lithosphere plate may be expected along and beneath the continental margin as a result of these high convergence rates. Lithologic evidence from deep-sea drilling holes on the Nazca Plate also suggests a uniform and rapid convergence rate for this region during the past 5 million years (Kulm et al., 1975a).

The occurrence of shallow (0-70 km), intermediate (70-300 km), and deep focus (300-700 km) earthquakes within the convergent boundary suggests that some type of subduction process is taking place along the Peru Trench (Stauder, 1975). From recent geologicalgeophysical studies (von Huene, 1972; Grow, 1973; Kulm _et al._, 1973) and earthquake studies (Isacks and Molnar, 1971; Barazangi _et al._, 1972; Oliver _et al._, 1974; and Stauder, 1975) it is now apparent that the oceanic lithosphere is being subjected to large scale underthrusting in the vicinity of the trench axis. Some of the uppermost crustal material (mainly sediments) is being transferred from the oceanic plate to the continental margin during this process (Seely, 1974; Kulm and Fowler, 1974; Kulm _et al._, 1974; Karig and Sharman, 1975). Accretion of oceanic sediments and deeper crustal material to the oceanic plate during the subduction process has been postulated by many investigators. For example, Seely _et al._ (1974) point out that 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. Kulm and Fowler (1974) show that during late Cenozoic time a substantial amount of continental accretion occurred as the result of underthrusting of Cascadia Basin deposits beneath the Oregon continental margin.

Thrusting and Accretion

Recent studies of the Peruvian continental margin with seismic reflection and refraction techniques suggest that underthrusting occurs as a result of the interaction of the Nazca Plate and continental South America Plate. Thrusting has been proposed within the Nazca

Plate at 12°S on the basis of seismic refraction work (Hussong et al., 1973). A model was proposed by Prince (1974) and Prince and Kulm (1975) to explain the development of imbricate thrust sheets in the axis of the Peru Trench between 6° and 10°S. The thrust sheets also involve the basaltic basement. Rosato (1974) and Kulm et al. (1974) showed that some of the sediments found immediately landward of the Peru Trench (i.e.: along the continental slope) are accreted Nazca Plate and Nazca Ridge sediments. Multi-fold seismic reflection data indicate an imbricate thrust fault system begins in the basaltic crust of the trench and extends landward under the continental slope (Kulm et al., 1975). Reverse faults in the sedimentary deposits of the upper continental slope off southern Peru suggest compressional forces which are interpreted as underthrusting and imbricate accretion on the lower slope (Johnson et al., 1975).

Coulbourn and Moberly (1975) also suggest that the structure of the continental margin off southern Peru and northern Chile "is consistent with a model of subduction of the oceanic lithosphere plate and obduction of a portion of its sedimentary cover." Apparently they used the word "obduction" instead of accretion as used here.

Focal mechanisms and the seismicity along the Peruvian continental margin indicate subduction of the oceanic plate beneath the continental plate. Underthrusting of the continental plate occurs along a thrust plane that dips 10°-15° beneath the continent (Stauder, 1975). The upper portion of this thrust plane is seen beneath the continental slope in multifold seismic reflection records made off central Peru (Kulm _et al._, 1975). If underthrusting is taking place along and within the Peruvian continental margin, deformation and uplift, associated with the subduction processes, may extend across the trench to the trench-slope juncture and beneath the continental slope. The structure of the continental margin basins suggests this is the case as will be discussed below.

The most obvious factors affecting the amount and style of accretion in a margin system are the nature of crustal rupture (i.e.: presence or absence of imbricate thrusts), time (e.g.: convergence rates), and availability of sediments on the oceanic and continental plates. The amount and relative proportions of various types of sediments (i.e.: pelagic versus terrigenous) fed into the subduction zone and to the upper continental slope determine the shape and size of the accretionary prism. Sediments that are incorporated into the accretionary prism at the base of the inner trench wall may be derived from either side of the trench (i.e.: oceanic plate or continental plate). These sediments may be altered, mixed or deformed during the accretion processes (Kulm, von Huene et al., 1973). Therefore they are difficult to study and interpret.

Basin Migration

Terrigenous sedimentation along the Peruvian continental margin produces a thick sedimentary sequence in the Sechura, Salaverry, Pisco, Lima, and Arequipa Basins (see Distribution of Sedimentary Basins). A careful examination of the structure of these sedimentary sequences shows the history of tectonism (i.e.: the relationship between tectonism and sedimentation) on the Peruvian continental margin. Single channel seismic reflection profiles made across the Peruvian continental margin show a landward (eastward) and seaward (westward) migration of the axis of maximum deposition in the Salaverry, Lima and Arequipa Basins. These shifts in the axis of deposition are interpreted as the sedimentary response of tectonic processes (i.e.: uplift or subsidence) occurring along the edges of those basins. Figure 16 shows two hypothetical cases of migration of the axis of maximum deposition due to differences in the rate of uplift at the edges of the basins. However, uplift is not the only explanation to the migration and other solutions will be discussed later.

Continental Shelf Basins

In the Sechura Basin (Fig. 11) there are not enough seismic reflection records to determine the migration of the axis of

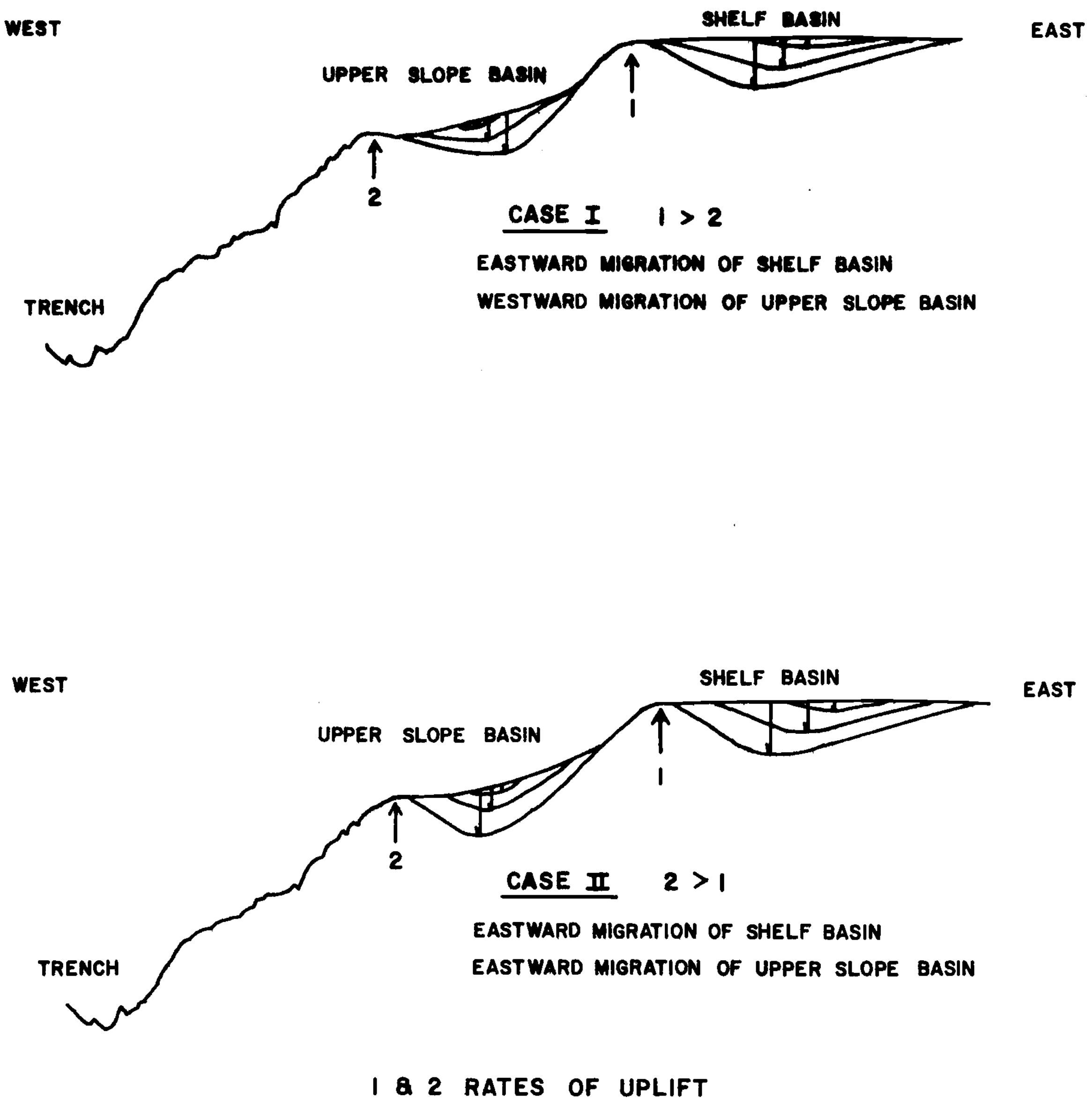

Figure 16. Hypothetical models showing migration of the axis of maximum deposition due to differences in the rate of uplift at the edge of the basins.

deposition. However, the sediments thin toward the outer continental shelf high which suggests continued uplift of the high (Fig. 12). In the Salaverry Basin the landward (eastward) migration of the axis of deposition suggests uplift of the outer continental shelf high. Thinning of the sediments toward the high suggests that uplift has been contemporaneous with deposition. Available seismic information is insufficient to show migration in the relatively narrow Pisco Basin. Nevertheless, the similarity of the characteristics of this basin setting compared with those of the Sechura and Salaverry Basins suggests that a landward migration may exist.

Alternatively subsidence processes may be postulated to explain migration of the axis of deposition, but it should be pointed out that subsidence implies downward (vertical) displacement with little or no horizontal displacement (component). To accomplish axis migration due to subsidence processes, it would be necessary to have a migration due to subsidence processes, it would be necessary to have a migration eastward of the basement faults causing the subsidence, and this seems unlikely. There is no evidence of faulting higher within the sediment section to indicate this basement displacement is occurring on the shelf. Therefore, the landward migration of the maximum axis of deposition, and the thinning of sediments toward the outer continental shelf high in the Sechura, Salaverry and Pisco Basins can be explained best by uplift of the outer continental shelf high.

Seismic reflection profiles made across the Peruvian continental shelf show a young sequence of flat lying sediments unconformably overlying older, gently warped synclinal deposits (e.g.: Fig. 13). This relationship and the fact that no seaward migration of depositional centers has been observed in basins on the continental shelf suggest that the older sequence apparently was deposited before the last cycle of the Andean orogeny (early Pliocene). Therefore, the younger sequence must be of Plio-Pleistocene age and the older sequence pre-early Pliocene. The main source area of these older sediments was probably to the west (the elevated outer continental shelf high). Landward migration of the basin axes suggests that the rate of uplift on the outer continental shelf during Mesozoic and early Cenozoic time was higher than that on the adjacent continent or that a rapid onbuilding of sedimentary sequences occurred in a basin which deepened asymmetrically to the east. This would imply a large sediment source to the west.

Upper Continental Slope Basins

A landward migration of the axis of deposition has been observed on lines 7 and 8 (Figs. 13-14) in the Lima Basin on the upper continental slope. On the other hand, a seaward migration has been observed farther south along line 10 (Fig. 15) in the same basin.

Farther south on the upper continental slope a landward migration is observed in the Arequipa Basin on line 26 (Fig. 17). The same phenomenon is reported by Coulbourn and Moberly (1975) for the extension of the same basin in northern Chile.

A migration of the axis of deposition in the basins on the upper continental slope can be interpreted in different ways and imply different tectonic events (Fig. 16). A seaward migration can be taken as the logical result of uplift of the outer continental shelf high or as a rapid outbuilding (progradation) of a sedimentary sequence in a basin which deepens asymmetrically to the west. A landward migration of the axis of deposition in the same basin can be explained by uplift on the seaward edge of the basin or by subsidence of the landward edge of the basin. The last explanation is not feasible because, as was pointed out previously, uplift apparently is occurring on the outer continental shelf high. Therefore, the landward migration of the depositional center in the upper slope basins along lines 7 and 8 in the Lima Basin and lines 25 and 26 in the Arequipa Basin suggest that uplift is taking place along the seaward edge of the basin and that the rate of uplift is presently higher than that of the outer continental shelf high.

The seaward migration noted along line 10 in the southern part of the Lima Basin may suggest that the rate of uplift on the outer continental shelf high is higher than the uplift on the seaward edge of

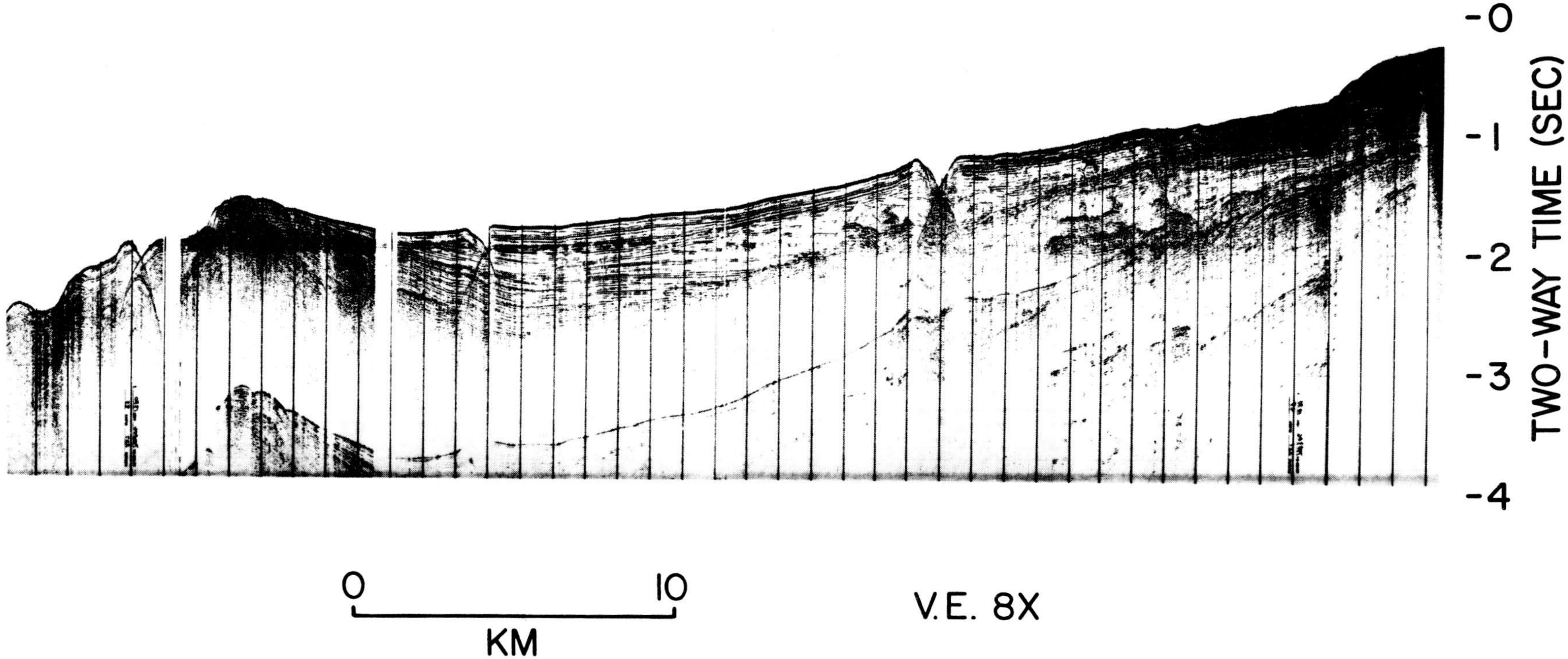

Figure 17. Seismic reflection profile 26. See Figure 11 for location.

the basin, or that the rate of sedimentation in the southern part is higher than the rate of uplift. These changes in the direction of migration of the depositional centers suggest that the rate and extent of tectonic activity varies along the Peruvian continental margin.

Relation of Seismic Activity to Margin Structure-Topography

Seismological studies have shown that the subduction zones off Ecuador, Peru and Chile are among the most active shallow seismic zones in the world (Oliver et al., 1974). Focal mechanism solutions indicate both strike-slip and thrust faulting with a maximum compressive stress oriented approximately perpendicular to the margin. Although the entire Peru Trench and margin are seismically active (Barazangi and Dorman, 1969), the total seismic energy released along the Peru Trench-margin is not evenly distributed. Kelleher (1972) studied the distribution of shallow focus earthquakes ($M > 7.7$) and found that the seismicity along the Peru-Chile Trench-margin apparently has a regional segmental character (Fig. 18). According to Kelleher (1972) the seismic gaps that occur in the northern Peru-southern Ecuador region (about 1°N - 9°S), southern Lima region (about 12.5°S to 14°S) and southern Peru-northern Chile (about 17°-25°S), "should be considered more likely location for large earthquakes in the near future than the zones of recent rupture."

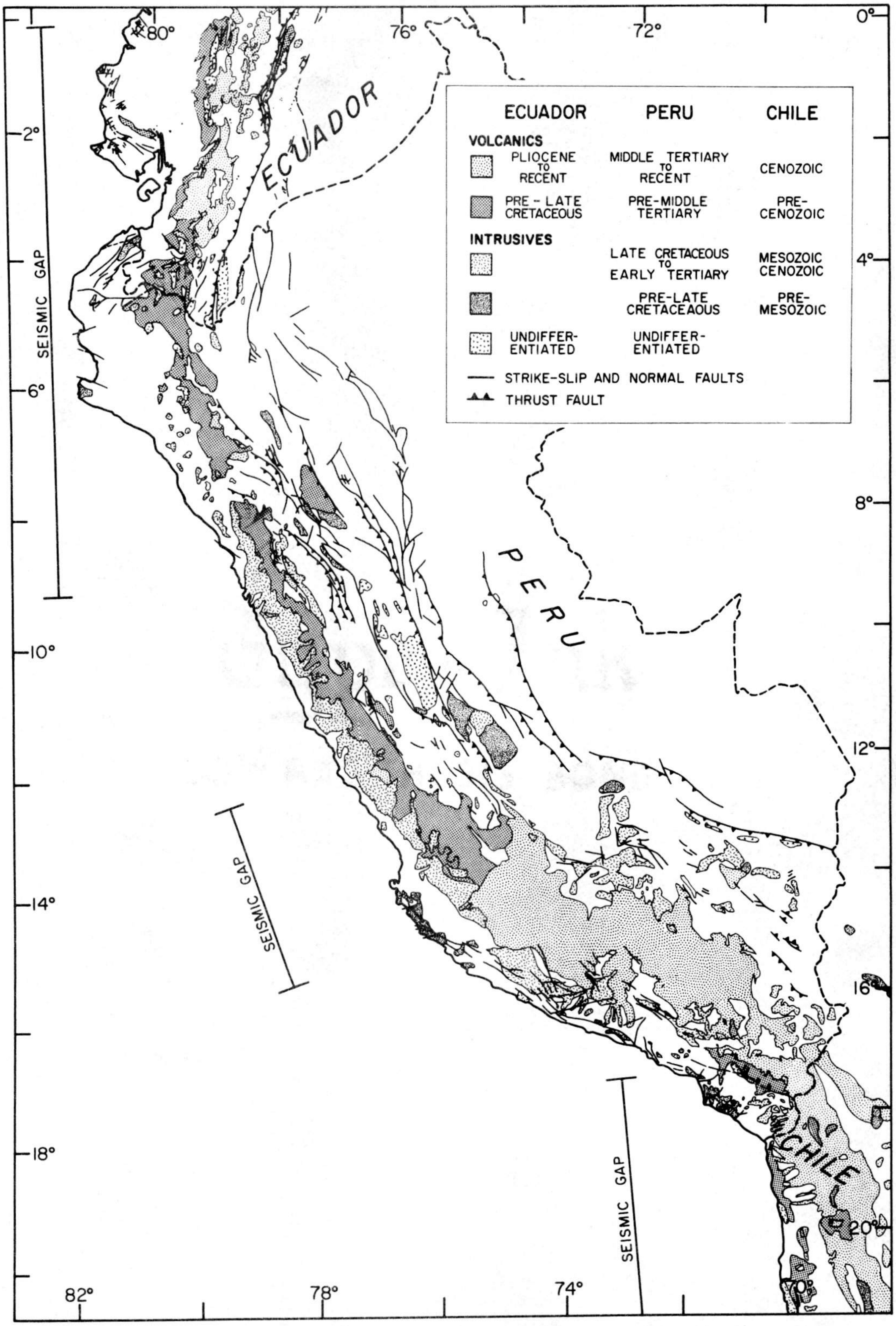

Figure 18. Seismic gaps (after Kelleher, 1972), structure and geology of Peru (after Prince and Kulm, 1975).

It is apparent that in the areas between the Kelleher's seismic gaps there is a continuous release of seismic energy. The large number of small magnitude earthquakes may reflect a continuous release of energy without appreciable rupture, which might produce a more gentle topography on the continental margin. On the other hand, the margin in the vicinity of the seismic gaps is probably under considerable strain at present, and a sudden release of this strain may cause substantial rupture and create areas with higher topographic relief.

A careful analysis of the bathymetric profiles along the Peruvian margin shows that, in general, there is a correlation between seismic gaps and topography. This suggests that topographic features on the continental slope are the result of tectonism associated with seismicity and subduction processes. In general, canyons seem to be fault controlled, while benches probably reflect the movement of thrust faults along the continental slope (Prince and Kulm, 1975). Furthermore, Kelleher's gaps show a good correlation with structural trends in the Andes (Prince, 1974). Between 4° and 8°S the Andes change from a northwest direction to the south to a northeast direction to the north (Fig. 19). This change is known as the Huancabamba Deflection (Ham and Herrera, 1963). On the continental margin opposite this area large canyons and numerous benches occur on the continental slope (Fig. 7, lines 1 and 2). Between

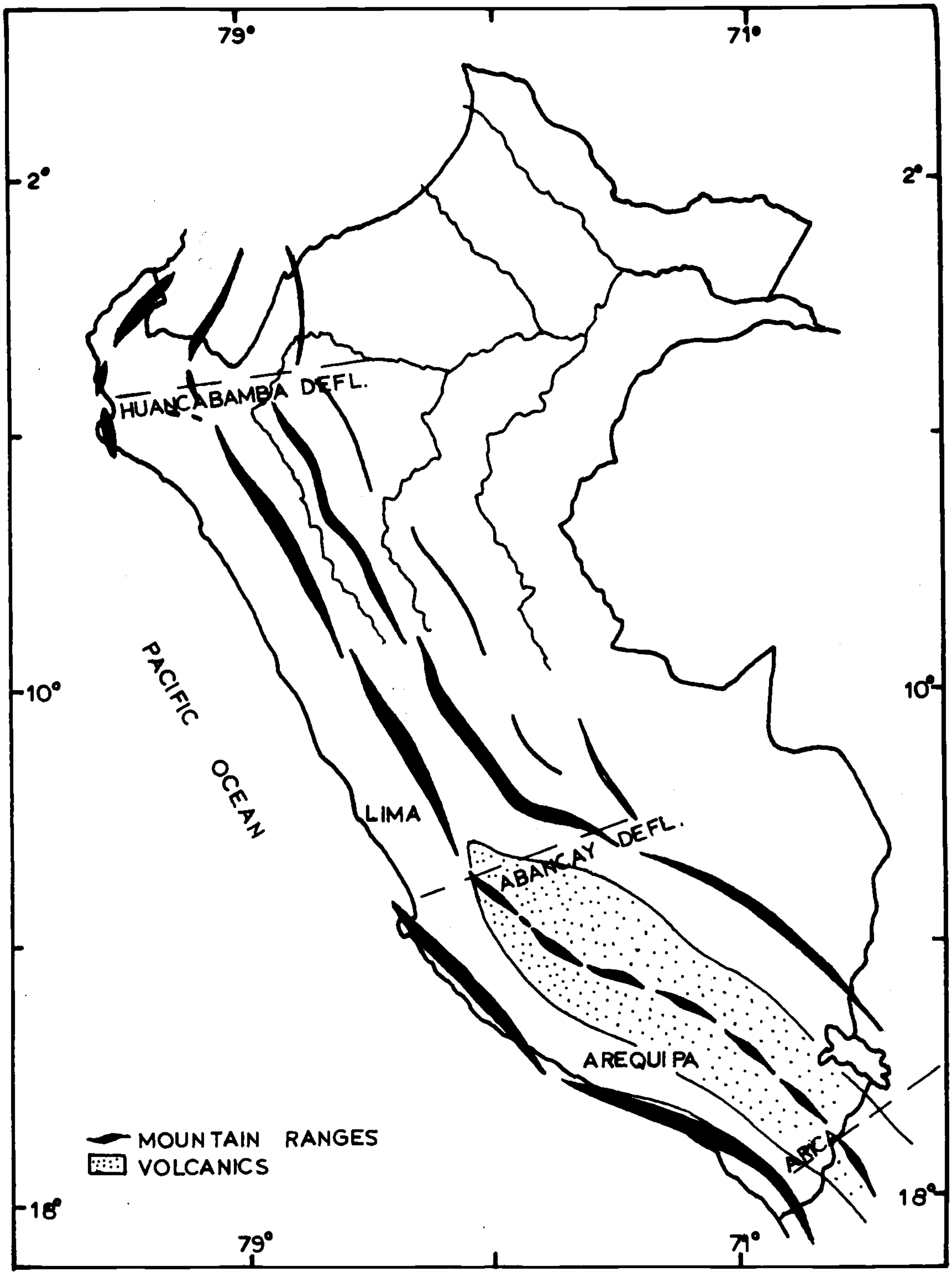

Figure 19. Mountain ranges of Peru.

9° to 12.5°S (an area between seismic gaps) the Andes trend in a northwest direction almost without change. This adjacent continental slope is generally characterized by gentle topography (Fig. 7, lines 8-10). The area from 12.5° to 16°S (seismic gap) coincides with a regional change in the trend of the Andes that has been called the Abancay Deflection. The Nazca Ridge is present in the offshore region and the continental slope is different to the north and to the south. In this area the continental slope is the narrowest, there are no sedimentary basins and the deepest regional shelf break occurs here. Although these structural characteristics may be associated with the presence of the Nazca Ridge (see section on Model, Stage IV), it is unlikely that a relationship exists between the Abancay Deflection and the Nazca Ridge. The seismic gap in southern Peru and northern Chile coincides with the Arica-Santa Cruz Deflection that shows a change in the direction of the Andes from northwest to north-south (Fig. 19). Offshore bathymetric lines in southern Peru (Fig. 7; lines 25 and 26) show a complex topography with numerous canyons, benches, and other features of high relief.

There is also a good correlation between the seismic gaps and the migration of depositional centers in the upper slope basins along the Peruvian margin (Fig. 11). Lines 7 and 8 in the Lima Basin show a landward migration of the centers and fall in the zone of continuous seismic activity (area between gaps), while line 10 shows a seaward migration and is located in an apparent seismic gap.

In southern Peru lines 25 and 26 show a landward migration and fall in a seismic gap. This apparent contradiction may be associated with a change in the direction of motion of the Nazca Plate and steepening of the Benioff Zone in southern Peru and northern Chile (Stauder, 1975). These observations, the seismicity along the Peruvian continental margin and the change of migration of the axis of maximum deposition in the basins in the continental shelf and continental slope of Peru suggest that the Peruvian continental margin is tectonically active, and that the tectonic activity varies along the margin.

MESOZOIC-CENOZOIC HISTORY OF THE PERUVIAN CONTINENTAL MARGIN

In the previous chapter the present day characteristics of the Peruvian continental margin were discussed using all the available onshore and offshore data. In this chapter an attempt will be made to show how the Peruvian continental margin attained its present day configuration through time. To do this, an assumption needs to be made. It is assumed that at Stage I in the proposed model the geology already reflected several ancient orogenic cycles along the Peruvian coast. The lack of information about Paleozoic and Precambrian events do not permit the interpretation of these ancient events. The proposed model, therefore, does not offer an explanation for the origin of Paleozoic and Precambrian features along the margin. Only the Mesozoic-Cenozoic history will be presented here and discussed in some detail in the following sections.

Model

Stage I

This stage describes the geologic conditions that existed just prior to the formation of the subduction zone along the west coast of South America. It is assumed that a boundary similar to that of the Atlantic type of continental margin (Heezen, 1974) existed then between the continental and oceanic plates (Fig. 20-I).

The Andean geosyncline developed near the western margin of the South American continent on a basement of pre-Mesozoic rocks of earlier diastrophic cycles. It was bordered on the east by a stable interior region and on the west (continental shelf) by a remnant belt which served as a borderland element or island arc (Steinmann, 1923; Benavides, 1956; Hosmer, 1959). The presence of this probable older high, that forms the present day outer continental shelf high off central Peru, is now fairly well documented by seismic reflection profile interpretations and unpublished drill hole data. It has been linked with the Amotape Mountains in northern Peru and the coastal range in southern Peru (Cobbing and Pitcher, 1971; Kulm et al., 1973). From seismic reflection profile interpretations, it appears that this high acted as a subaerially exposed positive element during Mesozoic and most of Cenozoic time. It has been recognized for some time that a source was required along the western border of the Andean geosyncline to provide the necessary detrital and volcanic material to the western part of the Cordilleran trough during Mesozoic time (Steinmann, 1923; Benavides, 1956; Isaacson, 1975). Weathering and erosion must have been an important factor in reducing this large elevated western source area to its present configuration, because a basement high still crops out at the edge of the continental shelf off northern Peru.

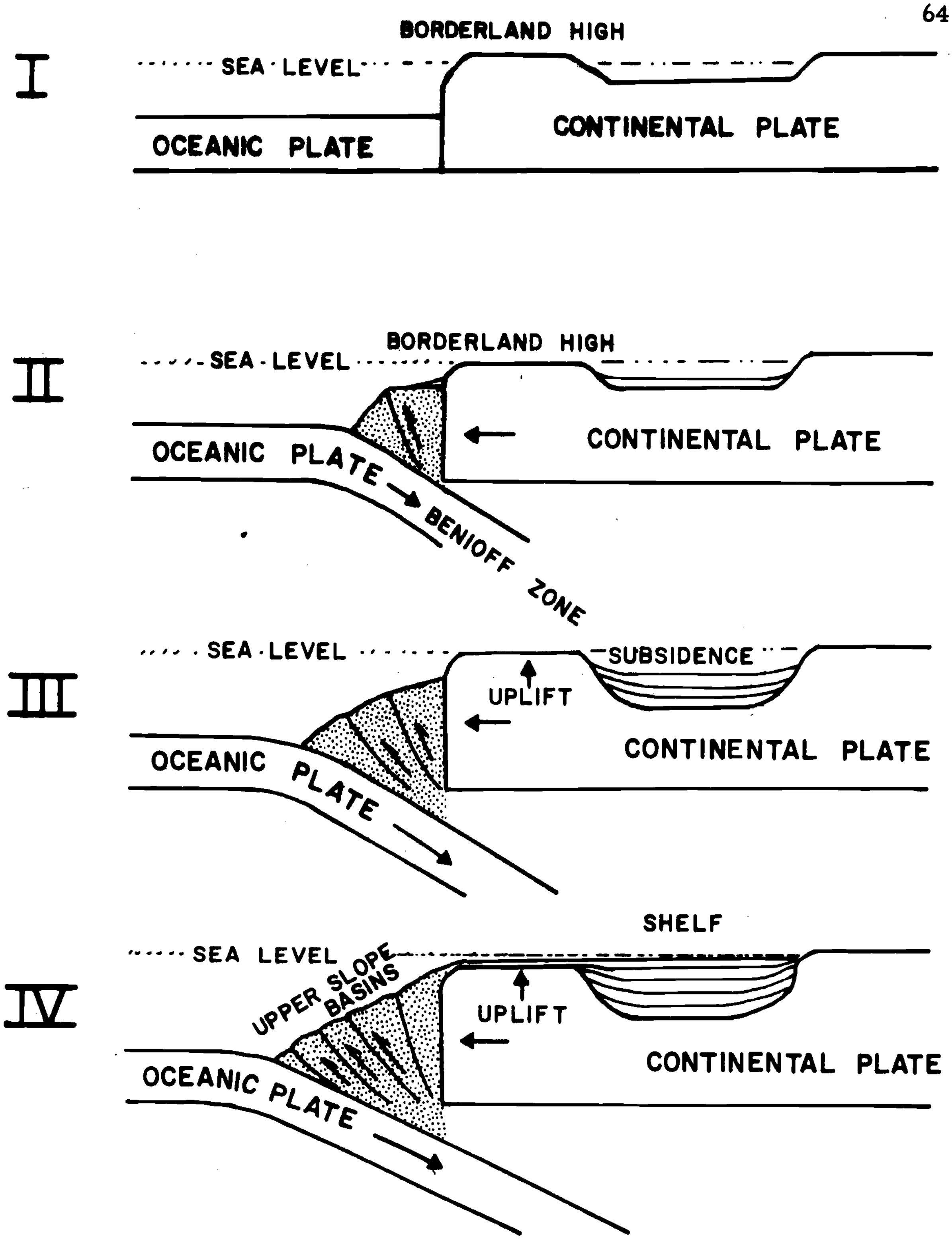

Figure 20. Four stage model showing evolution of the Peruvian continental margin. Stippled area is the accreted sedimentary prism. See text for discussion.

Stage II

Stage II begins with the development of the subduction zone along the west coast of the South American continent (Fig. 20-II). Assumptions based upon the time of the openings of the South Atlantic (Le Pichon and Hayes, 1971; Baumgartner, 1973) would suggest that the subduction zone developed about 140 m.y. ago. However, if one assumes that Mesozoic andesitic vulcanism in Peru is associated with subduction of oceanic crust at the boundary of two plates, the recorded volcanism and orogenic activity during Triassic-Jurassic time in Peru (Jenks, 1948; Cobbing and Pitcher, 1971; Stewart et al., 1974) suggest that subduction and therefore, plate collision have been active processes since at least 180 m.y. ago. This date will be used for the present study. In Stage II compressional forces due to plate collision caused thrust faulting along the boundary of the two plates. Trench sediments and material from the oceanic plate were scraped off into the continental margin (i.e.: the borderland arc) or subducted as a portion of the crystalline oceanic plate was thrust beneath the continental plate along the newly formed Benioff Zone (Fig. 20-II).

Onshore geology and regional structural trends suggest that during Early Jurassic time a basin existed along the Peruvian continental margin between the Marañon-Mantaro Geanticline to the east and a borderland located west of the present coastline (Benavides, 1956). During this period an alternating sequence of marine and continental sediments was deposited in this basin (Fig. 21).

Mesozoic volcanics form thick eugeosynclinal deposits in the coastal region of southern Peru and northwest Peru (Hosmer, 1959). The abundance of basic and intermediate volcanics, which is typical of a eugeosynclinal facies, in the western part of the Cordillera trough, and the general lack of volcanic debris in the eastern part suggest that the principal volcanic source was aligned along the west flank (borderland) of the trough. This borderland volcanism may have been the site of early intrusive activity due to the forming subduction zone. An eastward migration of magmatic foci has been documented by Stewart et al. (1974) on the basis of K-Ar age determinations in the coastal batholith of Peru. This would tend to substantiate the idea that igneous activity was initially centered in a western borderland area as proposed in the model.

Stage III

This stage is believed to be typical of middle to Late Cretaceous time. With the continued compression along the plate boundary new thrust faults developed along the boundary and the continental slope continued to build seaward by the accretion of oceanic plate material and by sediments of both marine (trench-margin deposits) and continental orgin (Fig. 20-III). The stratigraphy of Peru (Bellido,

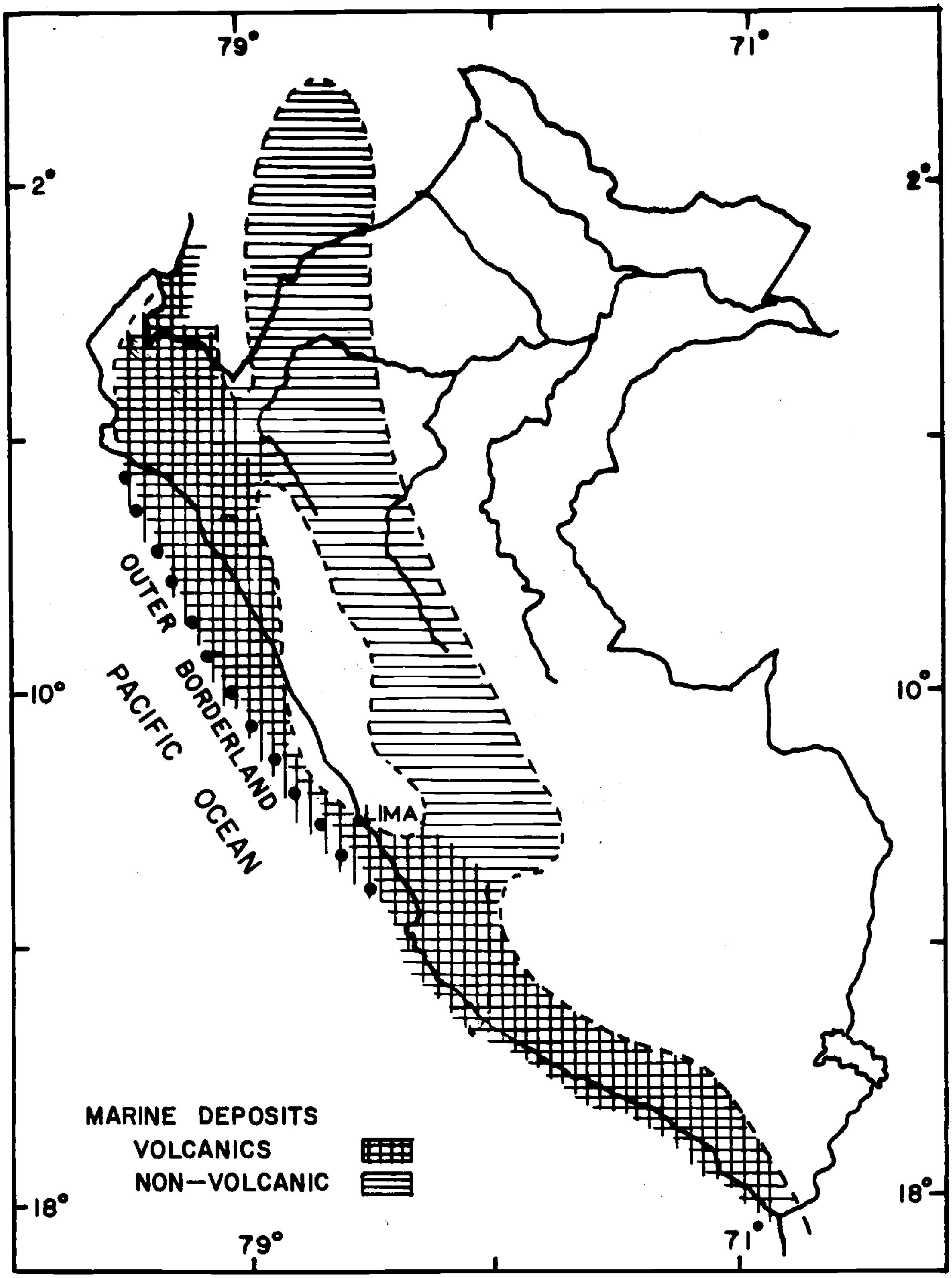

Figure 21. Paleotectonic map of Peru in the Early Jurassic (modified from Hosmer, 1959).

1969) shows that during middle Cretaceous time (Albian-Cenomanian) a marine transgression covered almost all of Peru. An alternating sequence of marine and continental deposits was deposited in a eugeosynclinal setting in the occidental (western) basin along the Peruvian coast (Fig. 22).

During Late Cretaceous time diastrophism in southern Peru restricted the marine conditions to northern and central Peru (Fig. 23). This episode of uplift is believed to be related to the initiation of folding in the present day Cordillera Occidental and to the initiation of the emplacement of the Andean batholith (Bellido, 1969). The uplift of southern Peru (south of about 14°S) may be the major tectonic event which produced the major difference in the structure and morphology of the present day continental margin off northern (6° to 14°S) and southern (14° to 18°S) Peru. During Late Cretaceous time the basins located to the east of the western borderland (present day coastal ranges) in southern Peru (south of about 14°S) remained in a high positive position. Subaerial erosion of the coastal ranges and the newly formed Cordillera Occidental was the source of the large amount of sediments that were deposited in the southern Peru Trench and probably subducted beneath the continent.

Meanwhile in northern and central Peru, the basins located to the east of the borderland high (present day outer continental shelf) continued to be filled with sediment from the high and from the

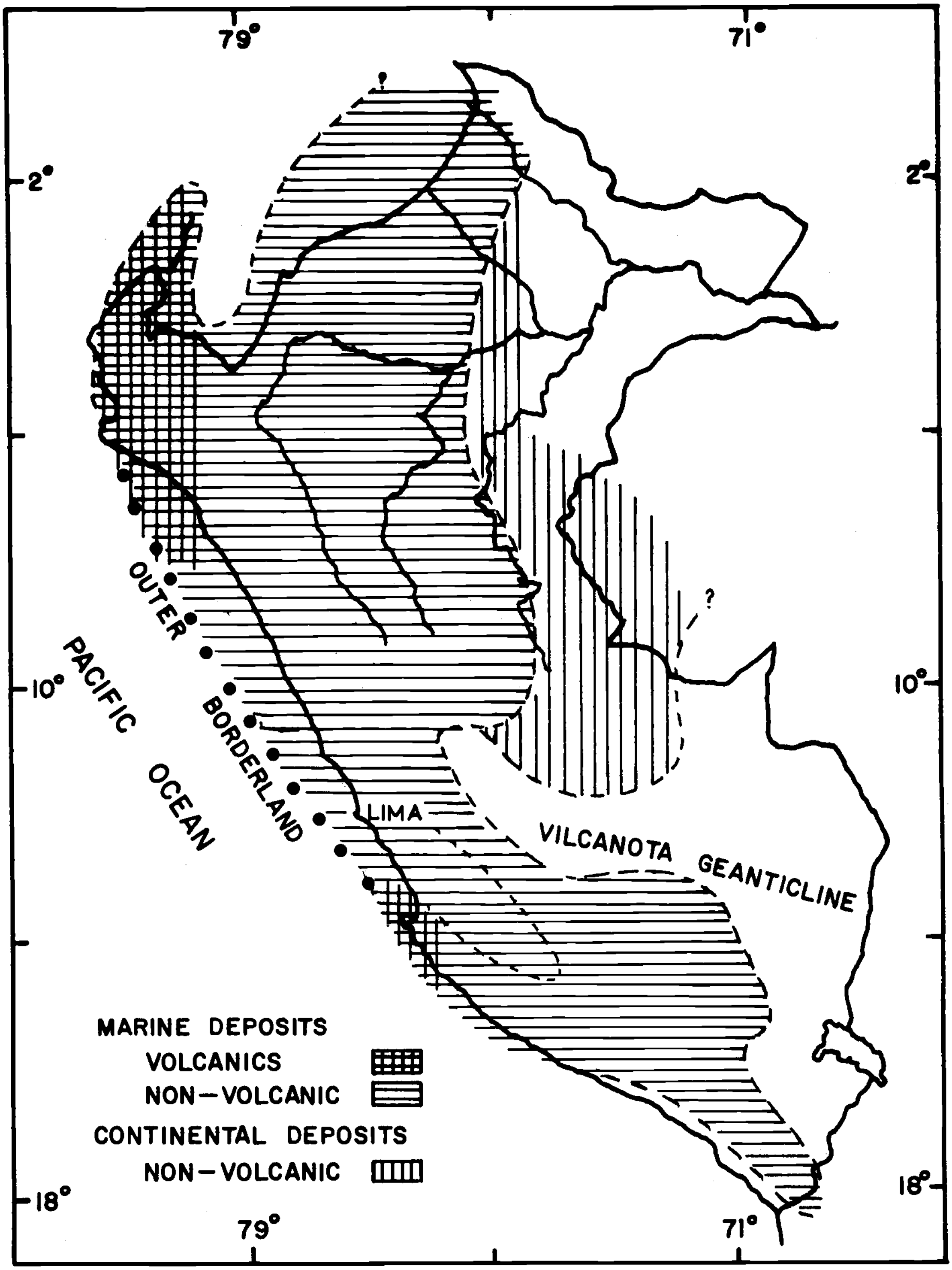

Figure 22. Paleotectonic map of Peru in the Early Middle Cretaceous (Albian) (modified from Hosmer, 1959).

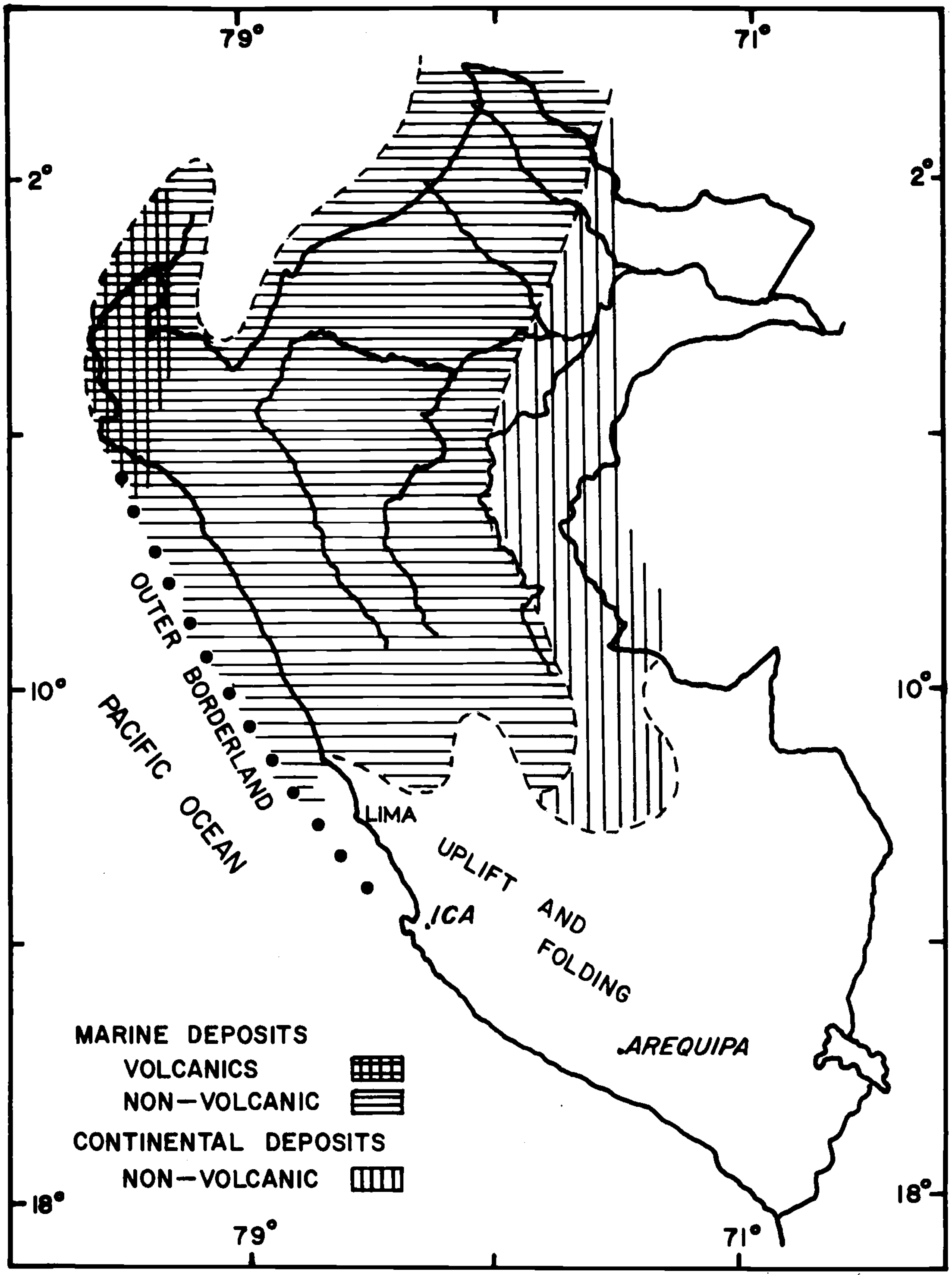

Figure 23. Paleotectonic map of Peru in the Late Middle Cretaceous (Turonian) (modified from Hosmer, 1959).

continent to the east. The outer shelf high also supplied material to the Peru Trench off central and northern Peru. However, the volume of material supplied to the trench is believed to be quite small. On the other hand, the amount of sediments supplied to the southern Peru Trench by the newly formed uplift areas and the existing coastal ranges must have provided a large volume of sediment for the trench in this area.

Stage IV

Geologic events that have taken place since Late Cretaceous time are associated with Stage IV. During Cenozoic time the Peruvian continental margin apparently attained its present configuration through continuous seaward growth of the continental slope and the build up of the sedimentary sequences found in the Sechura, Salaverry and Pisco Basins in central and northern Peru (Fig. 11). In Stage IV the emplacement of the Andean batholith, which had begun in the Late Cretaceous (Santonian) time (Bellido, 1969), and the second stage of the Andean orogeny (middle late Eocene), delineated the present day eastern boundary of the Sechura, Salaverry, and Pisco Basins.

During the Pliocene, debris from the second stage (middle late Eocene) of the Andean orogeny and the third stage (early Pliocene) of the Andean orogeny filled the Sechura, Salaverry and Pisco

Basins in central and northern Peru. These sediments were deposited in a shallow marine continental shelf environment. In the Pleistocene the several lowerings (regressions) of sea level caused erosion of the remaining topographically high areas on the continental shelf. The following transgressions deposited a large amount of shallow water sediments in the Sechura, Salaverry and Pisco Basins. These combined events produced the low relief topography that we observe on the Peruvian continental shelf today.

In southern Peru (about 14° to 18°S), the epeirogenic events that had begun in Late Cretaceous time, and the completion of the emplacement of the coastal batholith uplifted the marine basins to the east of the present Coastal Range. These basins were affected by intense volcanic activity during middle and late Tertiary time. This volcanism is believed to be associated with the large amount of sediments that the southern Peru Trench received since Late Cretaceous time. The nature of the relationship between the amount of sediments fed to the trench and corresponding land volcanism is still unknown. However, Prince (1974) postulated that "the most easily magmatized and mobilized portions of the subducted plate are the sediments and the upper weathered portion of the basaltic layer 2." Large amounts of subducted sediments might produce extensive arc volcanism.

It appears that the Lima and Arequipa upper slope basins were formed by the same continuous process which caused the continental slope to grow in a seaward direction. The deposits tectonically emplaced on the seaward flank of the basins may represent an earlier phase of thrust faulting during Stages II and III.

As was discussed previously between 14° to 16°S the morphology of the Peruvian continental slope is different to the north than to the south. This change is apparently associated with the presence of the Nazca Ridge which is believed to control the morphology of the adjacent continental slope. However, the extent to which this ridge is associated with tectonic processes occurring within the continental margin is still not well understood and additional work is needed to clarify the tectonic relationship between the Nazca Ridge and the Peruvian continental margin. Based on the model for the development of the Peruvian continental margin, it is hypothesized that the Nazca Ridge approached the Peruvian continental slope. It is believed that the Nazca Ridge could change the morphology of the margin in the following ways: 1) tectonically erode the accreted prism, 2) inhibit the growth of the continental slope by blocking the development of basins, and 3) by a combination of both processes. Evidence for some sort of change for this includes: 1) the width of the continental slope is different to the north and south of the Nazca Ridge (Fig. 24), 2) the continental shelf break is deeper in front of the Nazca Ridge than elsewhere on the margin (Fig. 25), 3) there is a lack of sediments and basins on the upper continental slope, and 4) the gradients

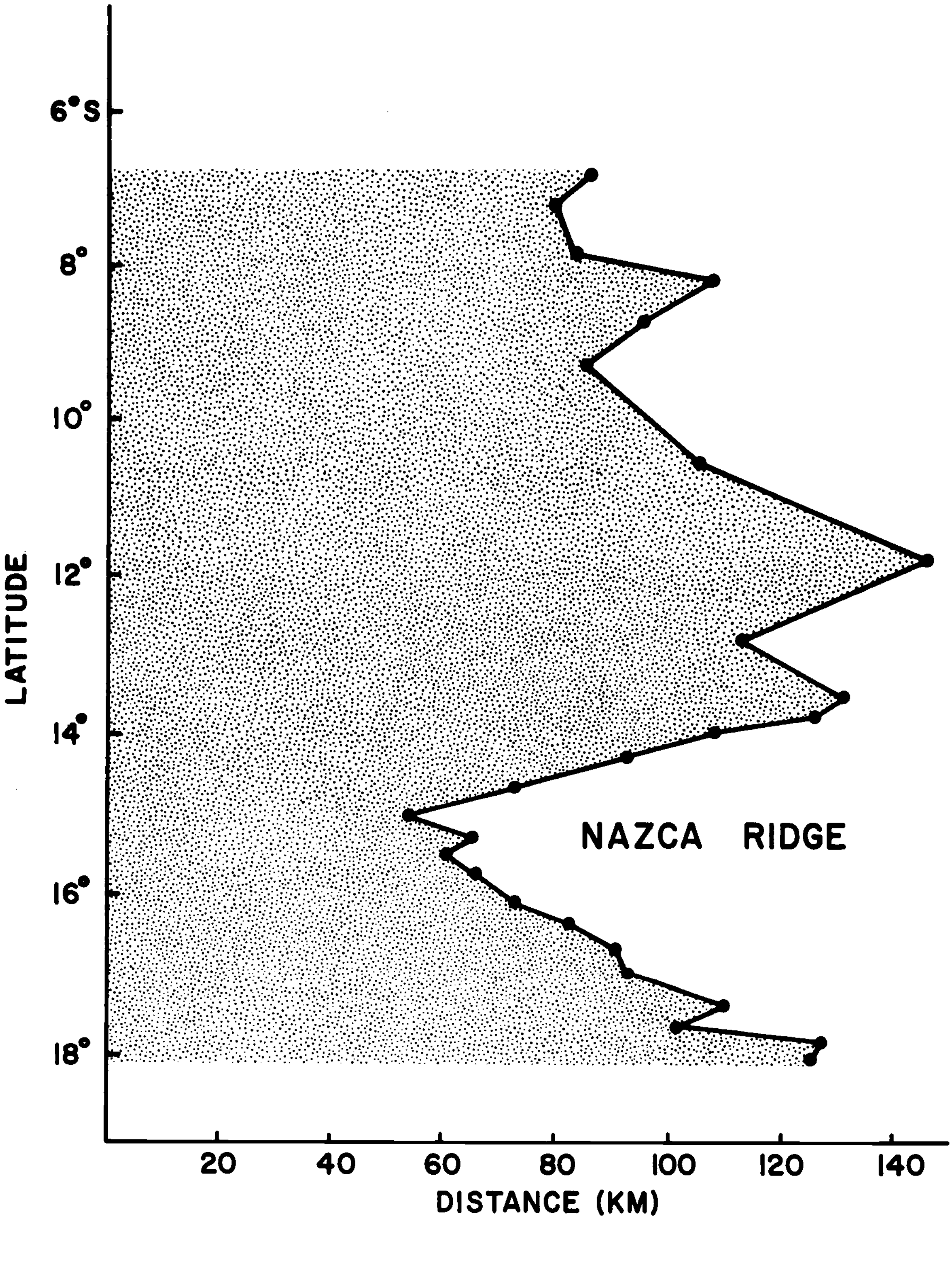

Figure 24. Width of the continental slope (stippled area) from the 200 m isobath to the trench axis, 6° to 18°S.

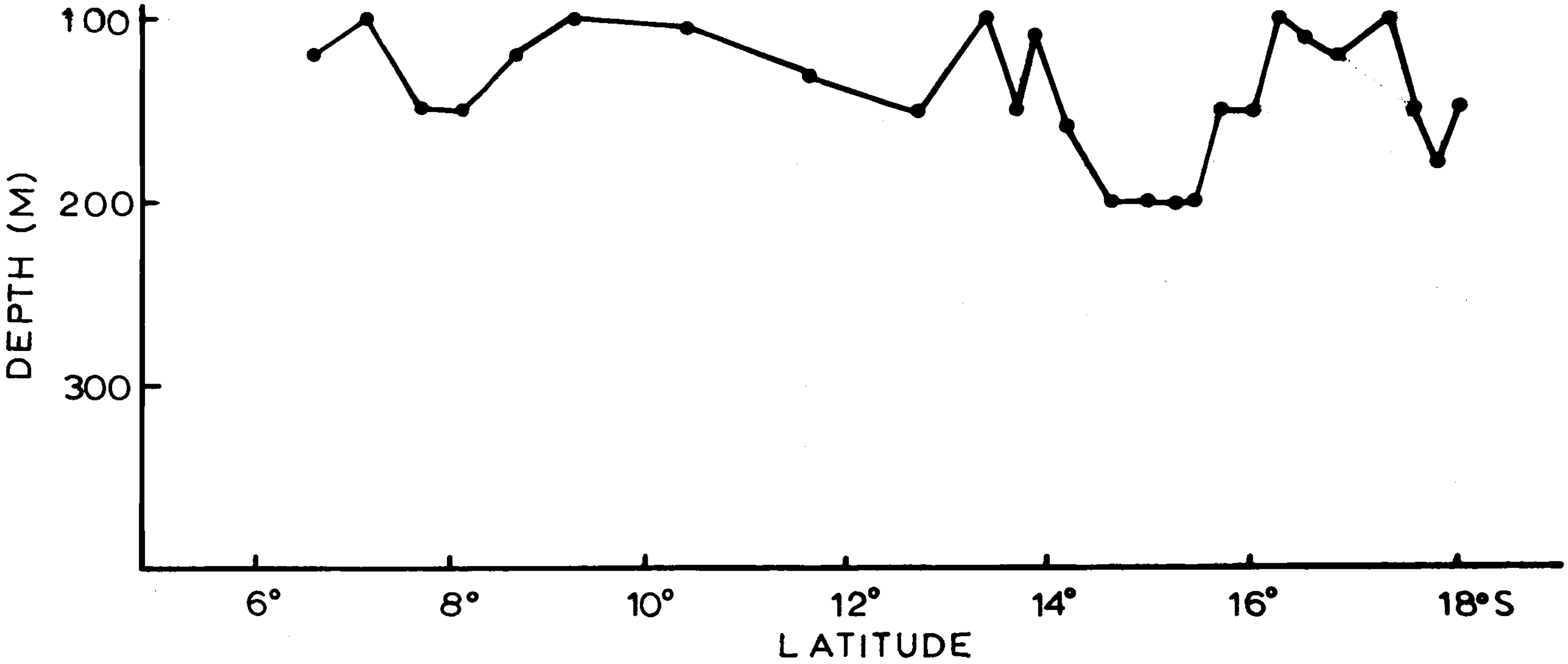

Figure 25. Continental shelf break along the Peruvian margin, 6° to 18°S.

are steeper on the continental slope adjacent to the ridge than the slope immediately north and south of the ridge.

Discussion

From recent investigations carried out by many scientists, and the present study, it appears that the Peruvian continental margin between 6° to 18°S is growing seaward by the following processes: 1) accretion of oceanic and continental sediments to the lower and middle continental slope through imbricate thrusting, and 2) deposition in tectonically formed upper slope basins (Lima and Arequipa Basins) which are being filled by terrigenous sediments derived from the continent. This accretion process begins in the trench through the rupture of the basaltic crust and sediments and extends landward beneath the continental slope in the form of imbricated thrust sheets (Prince and Kulm, 1975; Kulm et al., 1975).

It has long been recognized that there is a need for a large western land source area beyond the present-day western continental margin of South America (Steinmann, 1923; Benavides, 1956; Isaacson, 1975). In the proposed model (Stage I) this western source is considered to be a positive Pre-Mesozoic element, whose remnants are represented today by the outer continental shelf high (central Peru) and the Coastal Ranges (southern Peru). This western land source is believed to have been a center of andesitic volcanic activity which resulted from subduction along the newly formed Benioff Zone during Triassic-Jurassic time (Stage II). Radiometric dating by K-Ar in the coastal batholith of southern Peru does show an eastward migration of the magmatic axis through time (Stewart et al., 1974).

Assuming that the Mesozoic development of the Peruvian continental margin followed the pattern outlined in Stages I and II, it is possible to relate the major tectonics events (i.e.: uplift and folding) that took place in Late Cretaceous time (Stage III) to differences in morphology and structure that currently exist between the northern (6° to 14°S) and southern (16° to 18°S) Peruvian continental margin. Late Cretaceous volcanism in southern Peru is also possibly related to these events and together with the uplift of southern Peru caused the major input of sediments to the southern Peru Trench during Late Cretaceous-early Cenozoic time (see model, Stage III). It seems likely that subaerial erosion and denudation processes reduced the outer continental shelf high off central Peru to its present configuration. The proposed model, through Stages II and III, shows that a basin existed between the outer high and the continent to the east and that this basin was continuously filled with sediments which produced the filled basins on the continental shelf. Therefore, the presence of an older massif close to the edge of the continental shelf in central Peru is not embarrassing in terms of plate tectonics as Cobbing and

Pitcher (1971) indicate. The proposed model justifies and explains its presence in the Mesozoic-Cenozoic framework of the Peruvian continental margin and coastal region.

The lack of a so-called western land source along the present-day western margin of South America has led some authors to postulate that the continental block is being eroded by the subducting Nazca Plate along the Peruvian margin. The model shows that in Stages I to IV this is probably not the case. Furthermore, the Peruvian margin is undergoing accretion which suggests that tectonic erosion (i.e: removal of the continental block by subduction processes) of the leading edge of the South American Block is not really necessary to explain the evolution of the Peruvian continental margin. Trench sediments may be removed from the system or subducted beneath the continental plate without the removal of the crystalline crust of the continental block.

The geologic history of the Peruvian continental margin and coastal region (Stages I to IV) and the landward migration of the axis of deposition in the upper slope basins along the Peruvian margin suggest that there is a seaward shifting of the locus of uplift from the outer continental shelf high to the seaward edge of the basins in the upper slope. This is consistent with the seaward growth of an accretionary prism along the outer margin and the probable seaward migration of the trench axis.

Three geologic cross-sections were constructed for the Peruvian margin, based on the extrapolation of land geology, offshore seismic reflection profiles and the information discussed previously. Because of the lack of information about the offshore lithologies these sections are interpretations. In each of the three sections the accretionary prism extends from the base of the lower continental slope to the middle continental slope. Although this prism is documented by Kulm et al. (1975) using seismic reflection data, the amount of accretion cannot be determined precisely. The contact between the accretionary prism and continental strata (probably crystalline metamorphic rocks) is difficult to determine solely by interpretation of these data and will have to be resolved through new seismic reflection techniques and drilling. Accreted sediments beneath the lower and middle slope are believed to be deformed as documented for the eastern Aleutian lower continental slope (Kulm, von Huene et al., 1973) and probably affected by diagenetic processes. The sources for these continental sediments, which also include minor amounts of oceanic plate sediments, were the present-day outer continental shelf high (central Peru) and the coastal ranges (southern Peru). The terrigenous deposits probably consist of early-middle Mesozoic volcanics and Cenozoic continental detritus. Accreted sediments are no doubt youngest toward the trench and become progressively older landward. They appear to be partially covered by Plio-Pleistocene continental deposits which accumulate in small to large structural basins on the continental slope.

The northern geologic section is located at about 9°S over line 6 (Fig. 26). In this section it is possible to see in reflection records the outer continental shelf high which consists of probable pre-Mesozoic rocks, and the Salaverry Basin on the continental shelf. The basement of this basin may be Paleozoic and Precambrian rocks overlain by Mesozoic-Cenozoic sequences (Zuñiga and Travis, 1975). A normal fault system is present (Zuñiga and Travis, 1975) in the older shelf deposits and basement rocks due to subsidence and uplift in the outer continental shelf high.

The central section is located at about 12°S opposite Lima and is located along line 9 (Fig. 27). The outer continental shelf high is close to the coastline in this section, and the Paleozoic and Mesozoic rocks are extrapolated offshore from nearby onshore geology.

The southern section is located at about 17°S along line 26 (Fig. 28). In this section the continental shelf is essentially absent and the remnants of the coastal range seem to be forming the basement of the upper slope basin which is probably overlain by Mesozoic and Cenozoic strata.

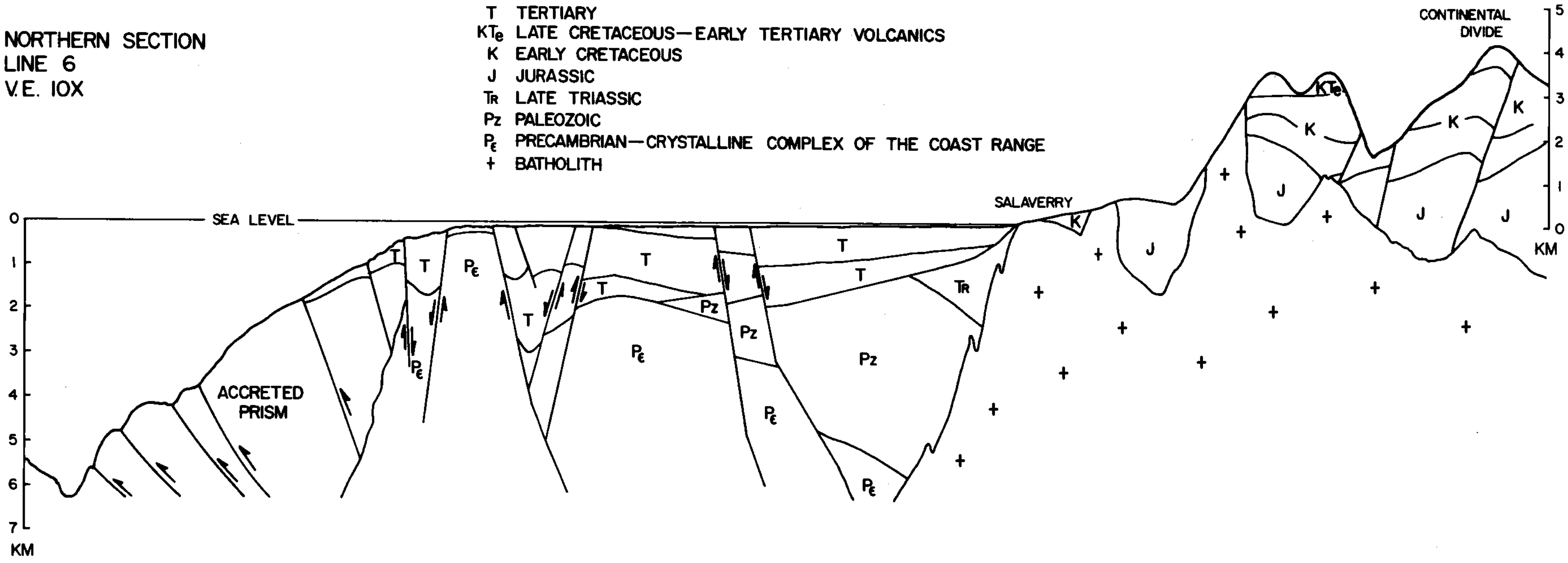

Figure 26. Generalized geologic cross-section along Line 6. See Figure 11 for location. Onshore geology from Bellido (1969); offshore geology inferred from onshore geology and seismic reflection data.

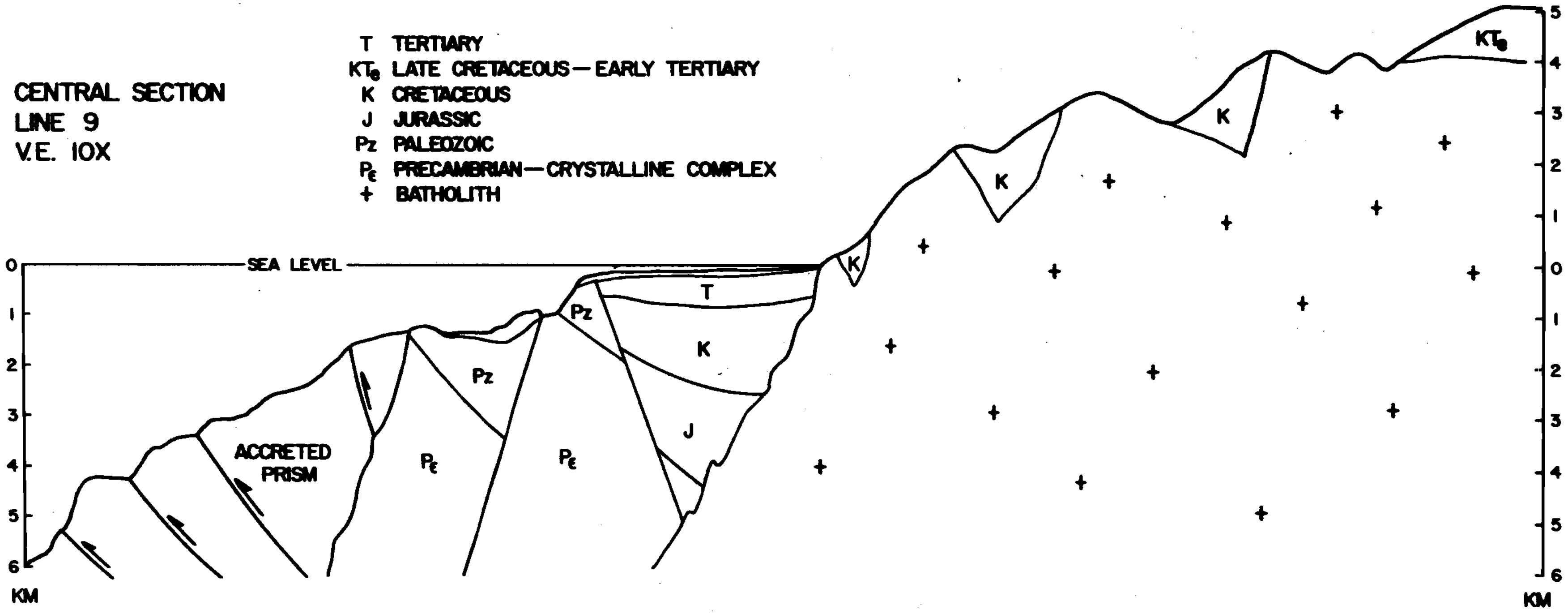

Figure 27. Generalized geologic cross-section along Line 9. See Figure 11 for location. Onshore geology from Bellido (1969); offshore geology inferred from onshore geology and seismic reflection data.

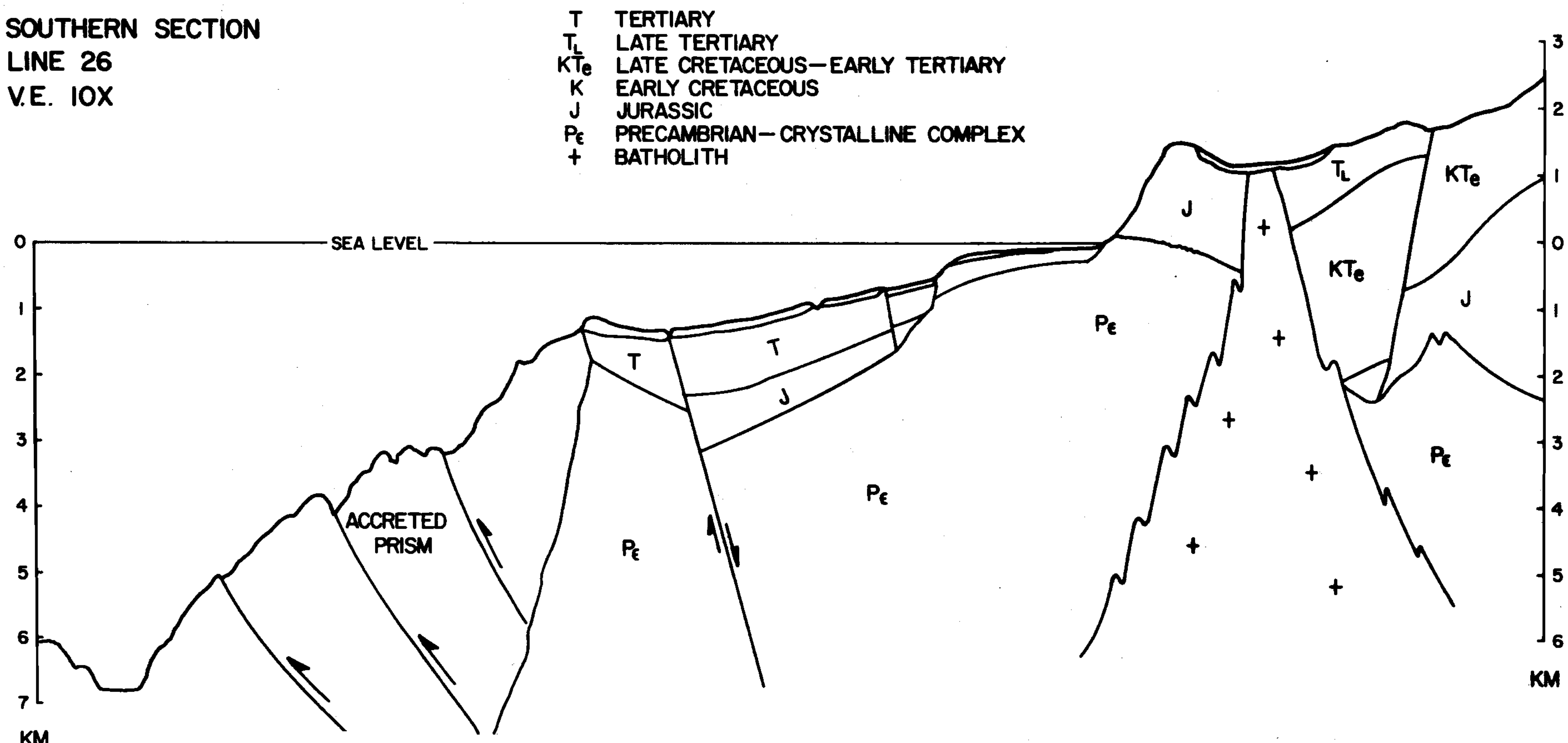

Figure 28. Generalized geologic cross-section along Line 26. See Figure 11 for location. Onshore geology from Bellido (1969); offshore geology inferred from onshore geology and seismic reflection data.

CONCLUSIONS

1. A new bathymetric map was constructed for the Peruvian continental margin (shelf and slope) and trench from 6° to 18°S by other investigators and the author. From this map and the individual bathymetric profiles one can see that the continental shelf is essentially flat, ranging in width from 5, off southern Peru, to 126 km off central Peru. The depth of the shelf break ranges from 100 m to 200 m, being deeper off southern Peru between 14° to 16°S.

The continental slope is divided into four physiographic provinces (A-D). The northernmost province (A) has an average width of 90 km and an irregular sea floor. Province B is characterized by the presence of the Lima Plateau and absence of large submarine canyons. Province C, opposite the Nazca Ridge, is narrow (average width 68 km) and the shelf break occurs at an average depth of 200 m. Province D is characterized by the Arequipa Plateau. The width of the slope averages 104 km.

The Peru Trench is separated into three provinces on the basis of regional depth differences.

2. Three basins, Sechura, Salaverry, and Pisco, are recognized on the Peruvian continental shelf between 6° to 18°S. Deposits range up to 6 km in thickness. These deposits probably range in age from Late Cretaceous to Tertiary (Zuñiga and Travis, 1975). Landward

migration of the axis of maximum deposition has been observed in these basins. This implies uplift of the outer continental shelf high.

3. Prominent basins occur on the upper continental slope off Peru (6° to 18°S). The Lima and Arequipa Basins have been named for their respective geographic position. These basins are filled with 1-2 km of probable Cenozoic deposits which overlie an acoustic basement consisting of probable older uplifted, accreted Nazca Plate and trench deposits.

4. Landward migration of the axis of deposition has been observed on the northern part of the Lima Basin on the upper continental slope. A seward migration has been observed in the southern part of the same basin. Farther south on the upper continental slope a landward migration is observed in the Arequipa Basin. These factors suggest that the rate of tectonic activity (uplift) varies along the margin and that the Peruvian margin is growing seaward by accretion. Multifold seismic data from the central Peru continental slope also confirm these conclusions (Kulm et al., 1975).

5. A four stage model for the Mesozoic-Cenozoic evolution of the Peruvian continental margin is proposed. Stage I describes the conditions that existed prior to the formation of the subduction zone. Stage II is marked by the development of the subduction zone about

180 m.y. ago. Stage III describes the development of the Peruvian continental margin through middle and Late Cretaceous time and uplift in southern Peru. Stage IV outlines the events that have taken place since Late Cretaceous time through Cenozoic time, and how the Peruvian continental margin attained its present configuration.

6. An outer continental shelf high exists off northern and central Peru and is defined by: 1) seismic reflection profiles, 2) extrapolation of onshore geology offshore, and 3) detailed free-air gravity anomalies of southern Peru (Whitsett, 1975). This high is believed to be composed of Paleozoic rocks with a possible Precambrian core below. This high is an important element in the proposed model for the Mesozoic-Cenozoic evolution of the Peruvian continental margin.

7. The Mesozoic-Cenozoic evolution of the Peruvian continental margin is compatible with plate tectonics theory. The model explains and justifies the presence of the outer continental shelf high off northern and central Peru. It allows us to conclude that the Peruvian continental slope is growing seaward and that continental erosion of the crystalline continental block is not necessary along the Peruvian continental margin.

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