AN ABSTRACT OF THE THESIS OF

Todd Mark Thornburg for the degree of Master of Science

in Oceanography presented on 30 September 1980

Title: SEDIMENTARY BASINS OF THE PERU CONTINENTAL MARGIN: STRUCTURE, STRATIGRAPHY, AND CENOZOIC TECTONICS FROM 6°S TO 16°S LATITUDE

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Abstract approved: L. D. Kulm

The morphology and shallow structure of the Peru continental margin has been mapped using bathymetric and seismic reflection profiles from 6°S to 16°S latitude. Other geophysical and geological data are used to constrain interpretations of the margin's deeper structure and to relate the offshore to onshore Andean geology.

Two prominent structural ridges, subparallel to onshore Andean trends, control the distribution of the offshore Cenozoic sedimentary basins. The Coastal Cordillera which surfaces north of 6°S and south of 14°S latitude can be traced onto the offshore as an Outer Shelf High (OSH); it is evidently cored with Precambrian and Paleozoic metasediments and crystalline rocks. A series of shelf basins are situated between the Coast Range/OSH and the Andean Cordillera: from north to south, these are the Sechura, Salaverry, and East Pisco Basins. A second set of upper slope basins flanks the Coast Range/OSH to the southwest, limited seaward by an Upper Slope Ridge (USR) of deformed sediment:

from north to south, these are the Trujillo, Lima, and West Pisco Basins. The Yaquina Basin lies within divergent arms of the USR. The shelf and upper slope basins are set on continental massif. An anastamosing network of elongate ridges and ponded sediments is the surficial expression of the subduction complex, which apparently begins just seaward of the USR.

The effect of the late Paleocene/Eocene Andean orogeny has been extrapolated offshore as a distinct interface of seismic velocity in the Salaverry Basin. Though Cenozoic marine sedimentation in the shelf basins did not begin until after this event, sedimentation in the upper slope Trujillo Basin may have been more continuous through the early Tertiary. In the Trujillo Basin, the bulk of the nearly 4 km thick sedimentary section is of Paleogene age, while in the adjoining upper slope Lima Basin to the southeast, the bulk of the nearly 2 km thick sedimentary section is of late Miocene or younger age. Apparently, post-Oligocene tectonism caused uplift, deformation, and a gross reduction of sedimentation in the Trujillo Basin; this event is evidenced by boundaries of differential structural deformation in seismic reflection profiles. In middle to late Miocene time, while orogenic activity affected the inland Andean Cordillera, the upper slope Lima Basin subsided and began its depositional record. Unconformities in shelf basins apparently reflect the inland tectonism at this time. The boundary between the Lima and Trujillo Basins, and between the contrasting styles of upper slope tectonic movement, is near 9.5°S latitude, coincident with the present day intersection of the Mendana Fracture Zone with the continental margin.

A final phase of upper slope deformation closed the Pliocene. Like earlier tectonic activity, the major break in structural style of this epoch occurs near 9.5°S: compressional faulting and folding characterize the younger sediments of the Trujillo Basin, while the Lima Basin appears as a broad, open syncline, disturbed only in its southernmost occurrence.

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STRUCTURE, STRATIGRAPHY, AND CENOZOIC TECTONICS
FROM 6°S TO 16°S LATITUDE

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1981

APPROVED:

Redacted for Privacy

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Date thesis is presented 30 September 1980

Typed by Pam Wegner for Todd Mark Thornburg

ACKNOWLEDGEMENTS

Many thanks to Dr. Vern Kulm who was always willing to give me the time, who was always adjustable to my erratic schedules, and who was flexible to my unconventional approaches and attitudes; thanks for providing orientation and direction, then letting me wander on my own (sometimes through the fog). Thanks also to my committee members, Drs. K. Scheidegger, A. Niem, and K. Ahearn for putting aside the time when time is at a premium.

Much obliged to my brother for introducing me to the science of "hammering rocks." Thanks, George and Vera, for a wild night sometime very late in 1954, where it all began. And thanks to all the oceanographic knuckleheads who make me laugh: Dave (qui es muy macho), Anne, Paul, Darrell, and Lynne.

Thank ya Sally Kulm for turning my crayon drawings into polished pen and ink drafts, and thank ya Pam Wegner for meeting my typing fire-drill with nimble accuracy. And thank ya Office of International Decade of Ocean Exploration, National Science Fondation (grants GX28675, IDOE71-04209, and OCE 76-05903) for keeping a roof over my head and food in my tummy.

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SEDIMENTARY BASINS OF THE PERU CONTINENTAL MARGIN: STRUCTURE, STRATIGRAPHY, AND CENOZOIC TECTONICS

INTRODUCTION

The Andes of Peru are unique when compared to many of the world's orogenic belts. Generally, Peruvian tectonic movements have been intracratonic: uplift and subsidence, basin formation and destruction have occurred in response to the vertical bobbings of block faulted continental crust (Myers, 1975). Thrusting is apparently superficial and subordinate (Myers, 1975) save for the eastern foothills of the Subandean foredeep; thick sedimentary turbidite sequences, melange, obducted ophiolites, and suture zones are lacking (Cobbing, 1978); and Precambrian craton-like masses are exposed at the coastline (Hosmer, 1959). Scars of collided continents, arcs, and accreted marginal ocean basins are not found in Peru. Simple oceanic subduction must somehow provide the mechanism for uplifting the Andean crust many kilometers above sea level, though perhaps collision is the final chapter in any orogenic record.

Inspection of a geologic map of Peru (for example, de Almeida and others, 1978) immediately emphasizes the strong linear nature of the orogenic belts which dominate the western part of the country and trend roughly parallel to the present coastline (Figs. 1, 2B). The geomorphic expressions of these features are, from southwest to northeast, the Coast Range, the coastal shelf and lowlands, and finally, the high Andes, heralded by the Coastal Batholith and folded Mesozoic sediments of the western foothills. The Coast Range is cored with Paleozoic metasediments north of 6°S latitude and Precambrian crystalline rocks

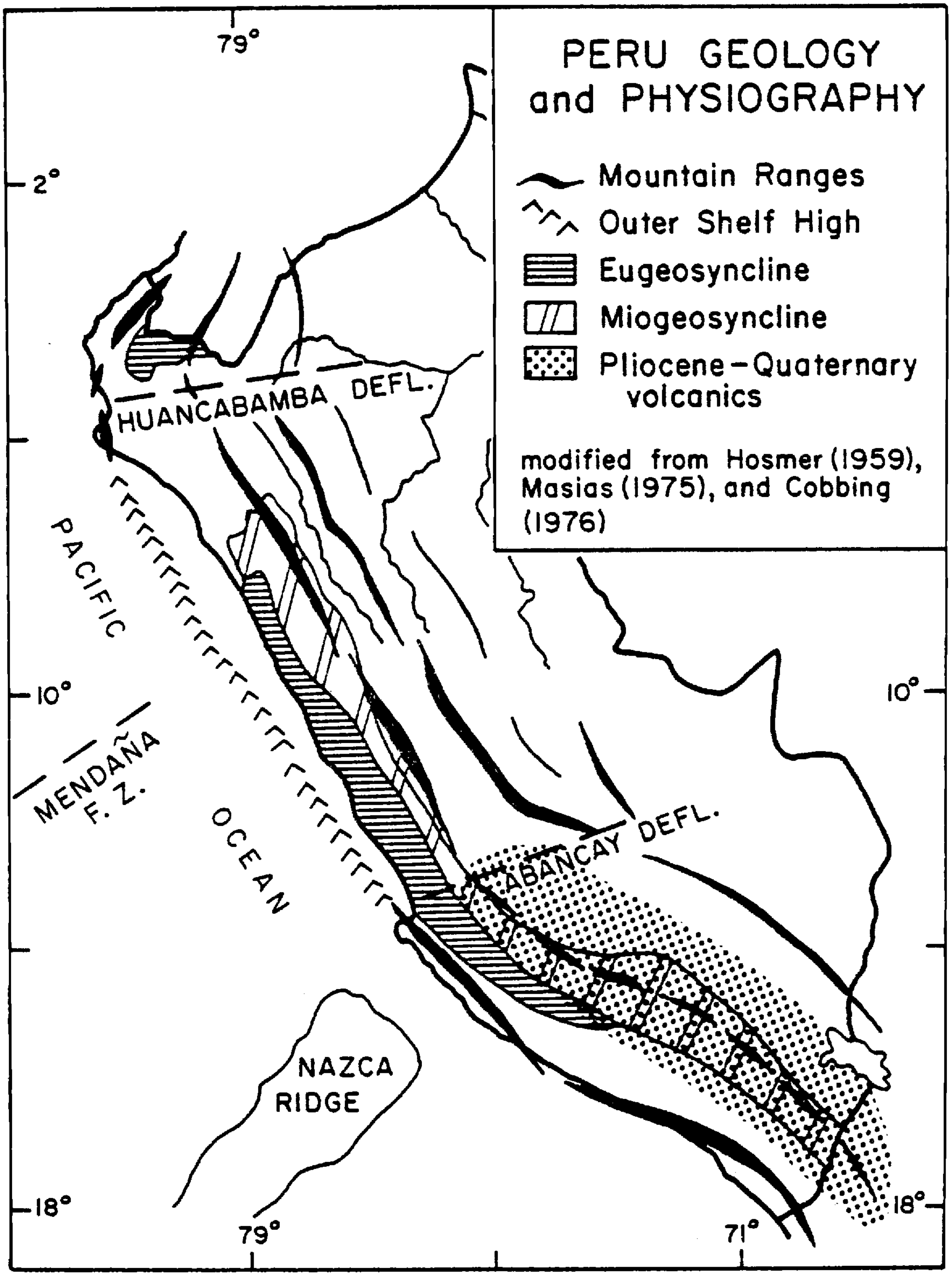


Figure 1. Structural trends, physiography, and geology (including present outcrops of Mesozoic geosynclinal deposits) of the Peru Cordilleran belt and neighboring offshore region.

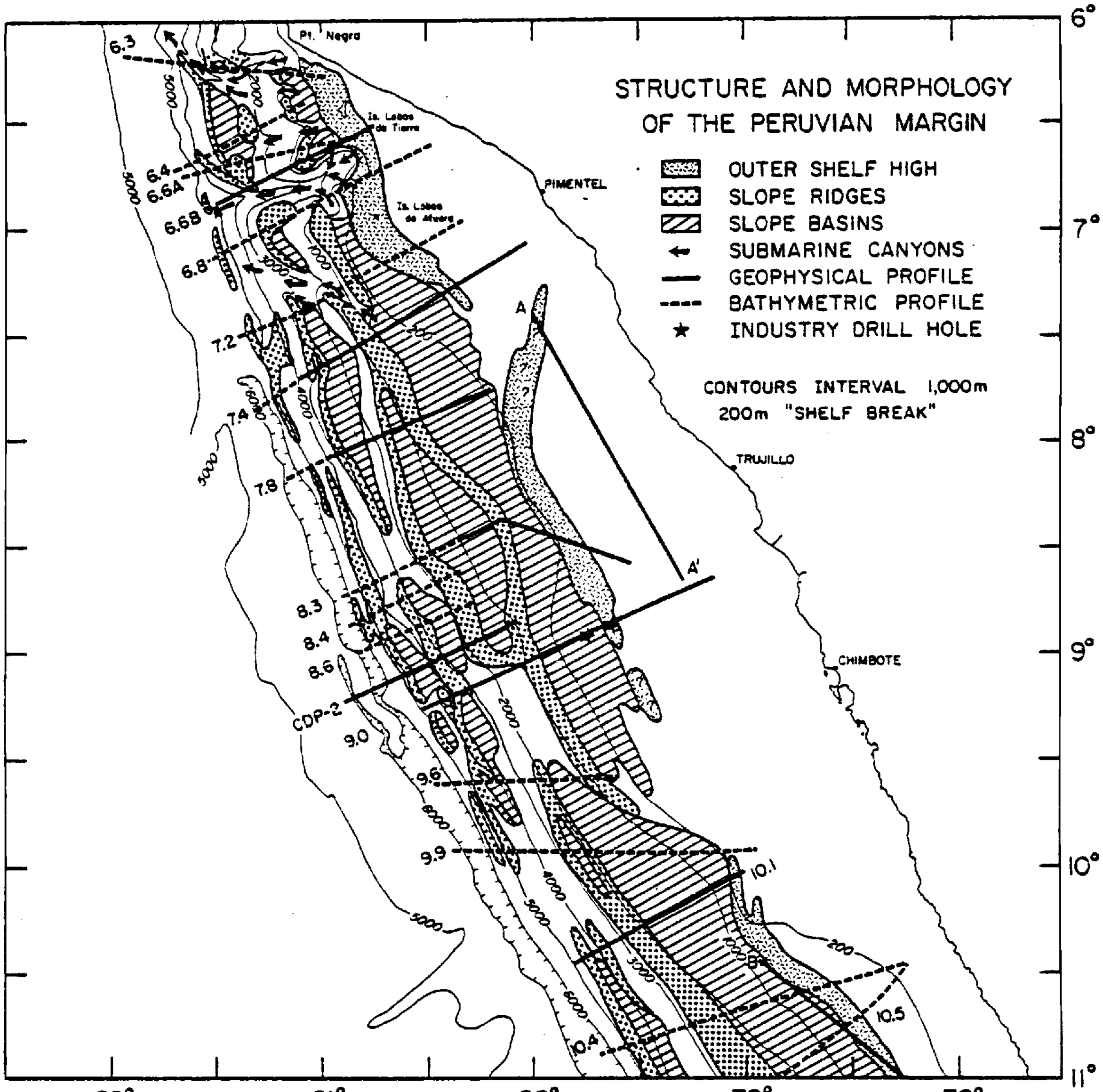


Figure 2A. Structural ridges, sedimentary basins, and submarine canyons of the Peru continental margin. Bathymetric and seismic control is plotted: profiles are referred to by latitudinal degree of intersection with the 200 m contour.

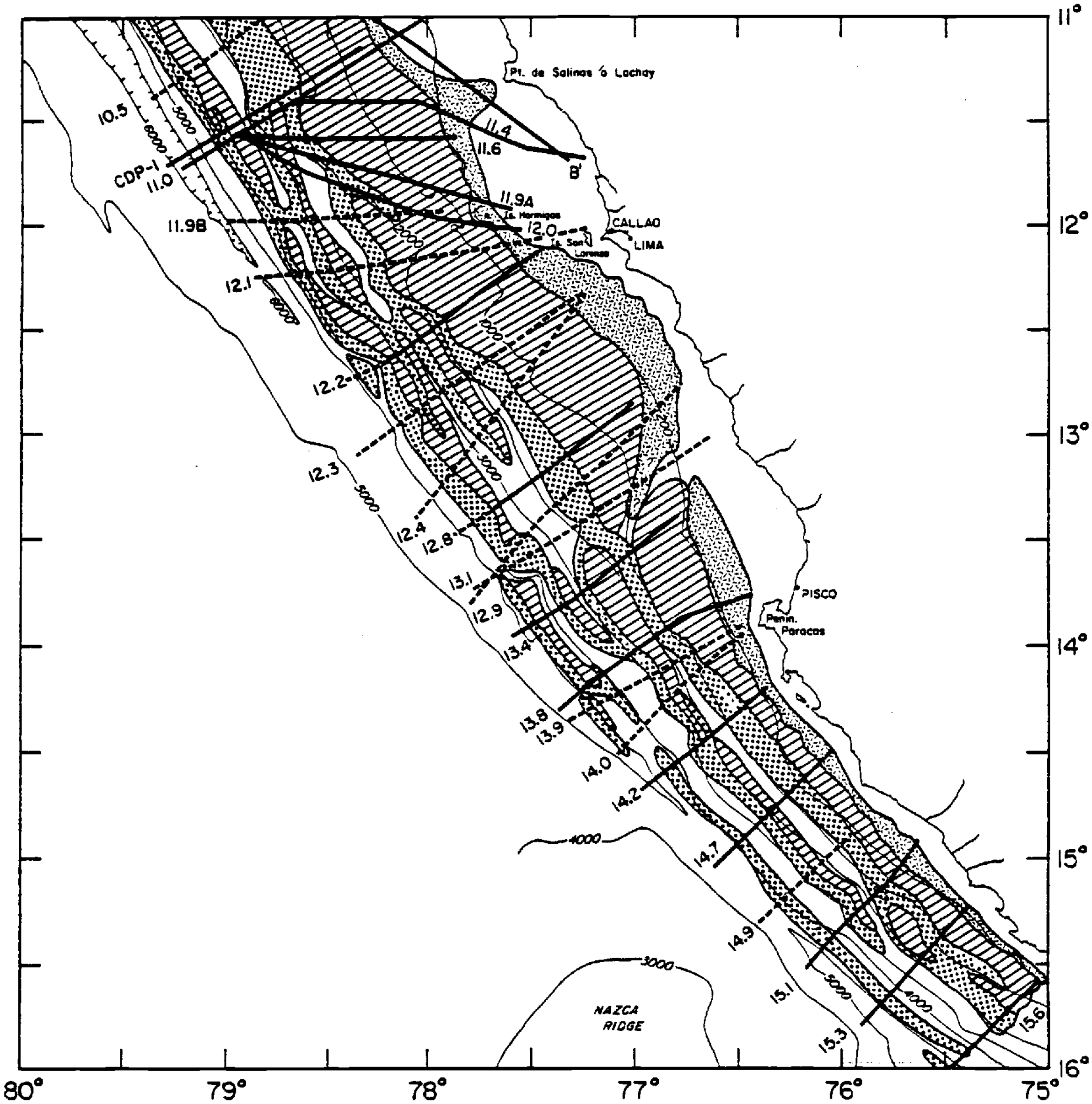
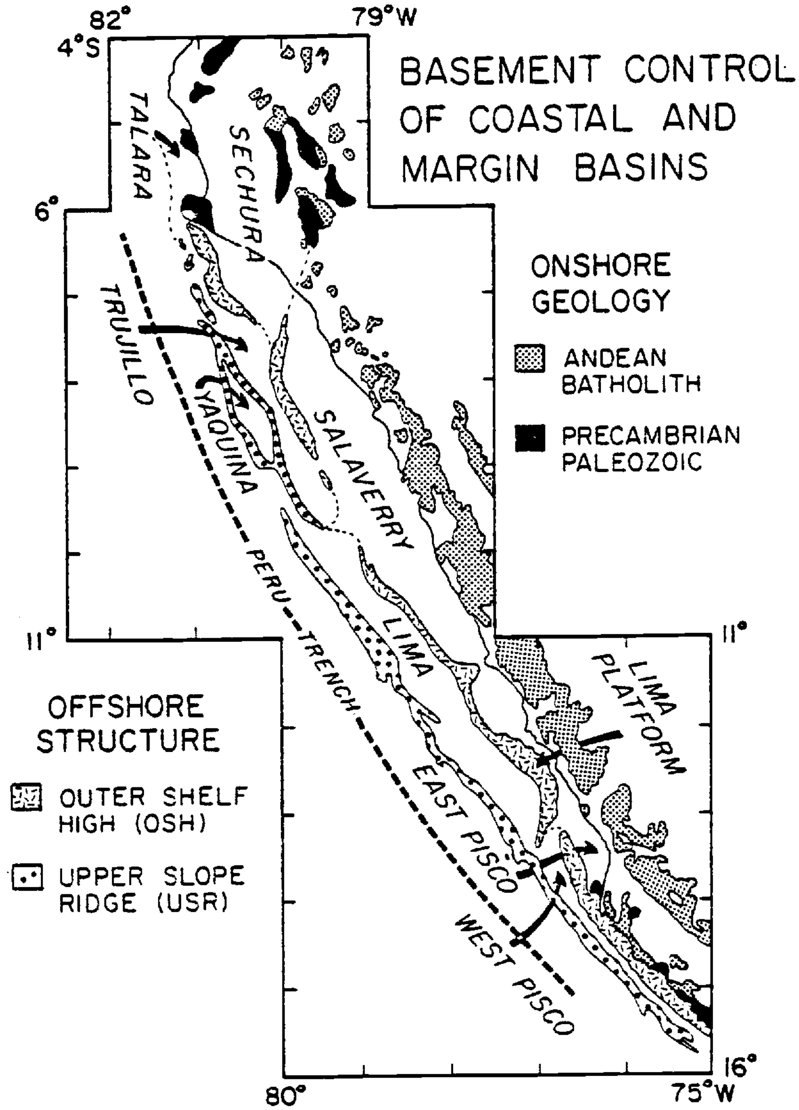


Figure 2A. continued.

Figure 2B. Major continental shelf and upper slope basins, and the onshore-offshore structures which control their distribution. The offshore OSH and USR are from Fig. 2A; onshore geology is from de Almeida and others, 1978. The flecked pattern of the OSH, and the stippled pattern of the USR have been standardized for annotation of all geophysical profiles used in this study (Figs. 4A through F, 5, and 6). Location map is shown below.



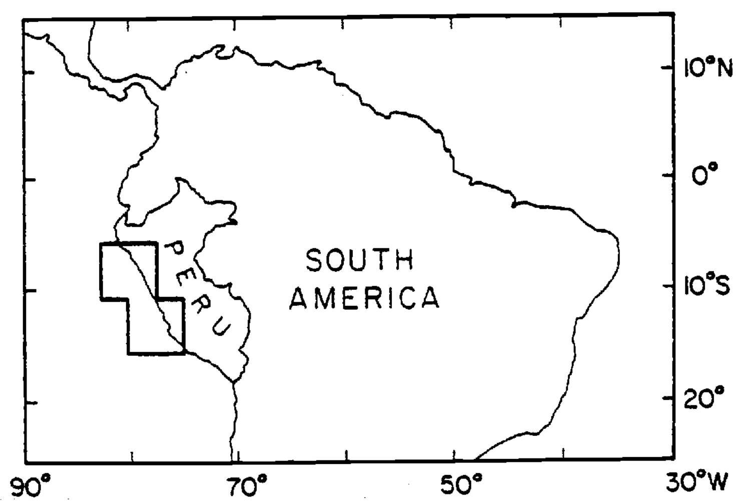


Figure 2B. Caption on preceding page.

south of 14°S; this resistant, pre-Mesozoic lineament forms prominent capes at these latitudes. In the intervening area, the sea has transgressed to the Andean foothills, submerging the Coast Range and coastal lowlands as a shallow shelf. The Coast Range, though, can be traced onto the continental margin as a fairly continuous outer shelf structural high (Masias, 1975; Travis and others, 1976; Kulm and others, 1977).

Distinct offsets and punctuations in Andean structural trends occur near these latitudes where the coastal mountains and plains become submerged, suggesting zones of transitional subduction tectonics. At 14°S near Pisco, the Abancay deflection intersects the coast, the extensive Quaternary volcanics of southern Peru terminate, and the aseismic Nazca Ridge abuts the Peru-Chile Trench (Fig. 1). To the north near 5°S, the Huancabamba Deflection describes the abrupt juncture of the northwest trending Peruvian Andes with the northeast trending Andes which continue into Ecuador (de Almieda and others, 1978). This tectonic "super-unit" between 6°S and 14°S is the focus area of the present study.

Our goal is to synthesize a coherent regional description of the structure and stratigraphy of the offshore basins of the Peru margin. We have established the geographical distribution of these basins, and delineated the structural ridges which confine them. Our research shows that the major forearc basins which occupy the shelf and upper slope lie entirely within the continental massif; thus, a comparison of lithologies, events, and deformational styles with onshore geology seems especially pertinent. An understanding of Andean evolution, then, is a prerequisite to understanding the patterns of sedimentation and tectonics in the basins of the Peru continental margin.

GEOLOGIC HISTORY

The close of the Paleozoic era in Peru was marked by strong orogenic activity which increased in intensity seaward and culminated in a belt of folding, batholithic intrusion, and metamorphism at the edge of the present continental margin (Hosmer, 1959). Today, a record of this event is preserved in the core of the Coast Range and the outer shelf structural high (Figs. 1, 2B). The geologic record of the early and middle Triassic is apparently absent throughout the whole of Peru (Jenks, 1956).

Birth of the Andean structural trends occurred in Late Triassic time with the inception of a paired geosynclinal belt: a western eugeosynclinal facies (volcaniclastics, pillow lavas, interbedded shales and tuffs) and an eastern miogeosynclinal facies (limestone, sandstone, shale) (Fig. 1). Tension in the underlying sialic crust resulted in movements along near-vertical fractures and shear zones, which apparently controlled the formation and geometry of these depositional basins (Myers, 1975). The separation of eugeosynclinal and miogeosynclinal facies is distinct north of Lima; to the south these facies merge and interfinger. Maximum subsidence of the miogeosyncline occurred in Tithonian time (upper Jurassic), but the thickest accumulations of eugeosynclinal deposits were not until Albian time (lower Cretaceous) (Cobbing, 1976).

The geosynclinal troughs formed in the shadow of a "continental-island arc" hybrid: volcanism was centered in a western geanticline at the toe or leading edge of the Peruvian craton, coincident with or very near the present Coast Range and outer shelf high of Paleozoic ancestry (James, 1971; Figs. 1, 2B). There is substantial geologic evidence for the existence of a western volcanic source which spewed huge thicknesses of dominantly andesitic volcaniclastics (several kilometers) from upper Triassic to upper Cretaceous time, concurrently with basic dikes which fed pillow lavas directly to the eugeosynclinal floor (Cobbing, 1978). Webb (1976) observed that many of the volcaniclastic units thinned to the east, while clast size also diminished eastward. Wilson (1963) documented E-NE paleocurrent directions from Valangian cross-bedded sands of the Lima area, and eastward dipping paleoslope features from the middle Albian near Chancay (11.5°S). Myers (1974) noted a facies change from submarine pillows and pyroclastic flows in the west to dominantly air or water transported pyroclastics eastward, also during Albian time. The eugeosynclinal volcanics rest directly on the sialic pre-Mesozoic coastal basement (Hosmer, 1959). The Paleozoic strata of the Coast Range north of 6°S are intruded by granitic rocks of pre-Cretaceous (probably Jurassic) age (Travis and others, 1976), and gneiss, schist, and Paleozoic strata of the Coast Range near 16°S are cut by quartz diorite intrusives which Stewart and others (1974) have dated at 204-157 m.y.; perhaps these intrusions represent the exposed roots of the fossil volcanic belt.

Geosynclinal conditions terminated in an upper Cretaceous spasm of uplift and batholithic intrusion which ushered in the Cenozoic with continental conditions. The Coastal Batholith in Peru is composed of hundreds of plutons which range in composition from gabbro to granite, tonalite being the most abundant (Cobbing and Pitcher, 1972; Pitcher, 1977; Fig. 2B). Preexisting basement fractures apparently exerted a strong control on the emplacement (Myers, 1975), which spanned the interval between 105 and 60 m.y. (Noble and others, 1979). Passive emplacement to within a shallow 5 km of the surface left sharp, uncomplicated contacts with narrow aureoles of contact metamorphism (Cobbing and Pitcher, 1972).

Deformation of the eugeosynclinal volcanics began as early as the Cenomanian, and pre-dated the intrusion of the Coastal Batholith (Hosmer, 1959). Structures were once again controlled by vertical movements of the underlying continental basement blocks: the volcanic strata are locally folded into tight, isoclinal synforms, presumably where they overlie vertical shear zones; elsewhere deformation is slight and bedding dips are gentle (Myers, 1975). The miogeosyncline was not deformed until the waning moments of intrusion in early Cenozoic time, after it had recieved a cover of coarse molassic debris from the rising volcanic belt to the west (Hosmer, 1959). Deformation was more extreme compared to the eugeosynclinal partner, but here, too, thrusting and overturned folds of general NE vergence are supposed to be the superficial response above a decollement surface to vertical, blocky basement activity (Myers, 1975). Interpretation of recent geologic and radiometric data has refined the timing of this tectonic event to within the late Paleocene and/or Eocene (Noble and others, 1979). Tectonic quiescence characterized the Oligocene, then major uplift and deformation resumed in middle/late Miocene time (between roughly 15 and 10 m.y. ago), accompanied and followed through the Pliocene by intense volcanism and plutonism (Noble and others, 1974; Farrar and Noble, 1976). This late Tertiary activity affected the eastern Andean ranges and the Subandean foredeep most directly.

There has been a progressive, though sporadic, eastward migration of magmatism during the evolution of the Andean continental margin:

from the Coast Range/outer structural high in the Mesozoic, to the Coastal Batholith in the early Tertiary, to the site of the deformed miogeosyncline in the late Tertiary. James (1971) rationalizes the migration as resulting from 1) progressive depression of isotherms along the subducting oceanic slab, 2) landward migration of the trench with time, or 3) progressive shallowing of the dip of subduction with time.

MORPHOLOGY AND STRUCTURE OF THE PERU MARGIN

Two persistent structural ridges are traceable along the Peruvian continental margin; these have molded the geometries of the major shelf and upper slope basins. The pre-Mesozoic lineament which rises above sea level to become the Coast Range near 6°S and 14°S is designated the Outer Shelf High (OSH) where it can be traced onto the continental margin. Its role as a geanticlinal locus of igneous activity during the development of the Mesozoic geosyncline has been emphasized (see Geologic History). Continued influence as a positive element during the Tertiary has allowed a set of shelf basins to accumulate between the OSH and the onshore Andean Belt. From north to south, these are the Sechura, Salaverry, and East Pisco Basins (Fig. 2B; Travis and others, 1976). To the west, a second set of upper slope basins is cradled between the OSH and a prominent Upper Slope Ridge (USR). From north to south, these are the Trujillo, Lima, and West Pisco Basins. The Talara Basin, to the north, lies west of the Paleozoic Coast Range and occupies a correlative upper slope position. The Yaquina Basin lies entirely within divergent limbs of the USR. The remainder of the Peruvian continental slope is laced with an anastamosing, interweaving net of structural ridges, and associated sedimentary basins which have backfilled landward of these ridges. In the north, this ridge and basin terrane is dissected by submarine canyons.

These structural/morphological features were correlated between geophysical profiles and geological sections, and delineated in map view (Fig. 2A). The bathymetry of the continental margin, contoured at a scale of 1:1,000,000 (Prince and others, 1980), was used as a base map. Numerous bathymetric profiles (arranged from north to south in Figs. 3A,B) and single channel seismic reflection profiles (Figs. 4A through F, from north to south) provided a bulk of the raw data, as plotted in Fig. 2A. These profiles were collected during Oregon State University's R/V Yaquina cruises (1972, 1974) and Hawaii Institute of Geophysics' R/V Kana Keoki cruise (1972).

Particular attention was given to mapping the influential Outer Shelf High (OSH) and Upper Slope Ridge (USR). Bathymetry is usually inadequate to establish the presence of the OSH. Very often, the USR controls the first significant gradient increase which can realistically be called a shelf break. As a result, the subsurface meanderings of the OSH are often hidden beneath the flat and featureless morphology of the continental shelf. [Note: regardless of the position of the shelf break, those basins which lie between the OSH and USR are referred to as upper slope basins, those between the OSH and the Andes are referred to as shelf basins.] In contrast, the basins and ridges of the continental slope (including the USR) are morphologically expressive. Once these features have been ascertained in seismic reflection records, they can be extrapolated onto bathymetric profiles with reasonable confidence (Figs. 3A,B).

The OSH can often be recognized from seismic reflection records as

Figure 3. Bathymetric control (prefix BP in text) used in Fig. 2A. Seismic control (prefix SP; Figs. 4A through F) is also shown here in bathymetric form. Profiles are arranged from north to south. (Note: the double line parallel to the sediment surface used to indicate a sedimentary basin does not imply subsurface structure.)

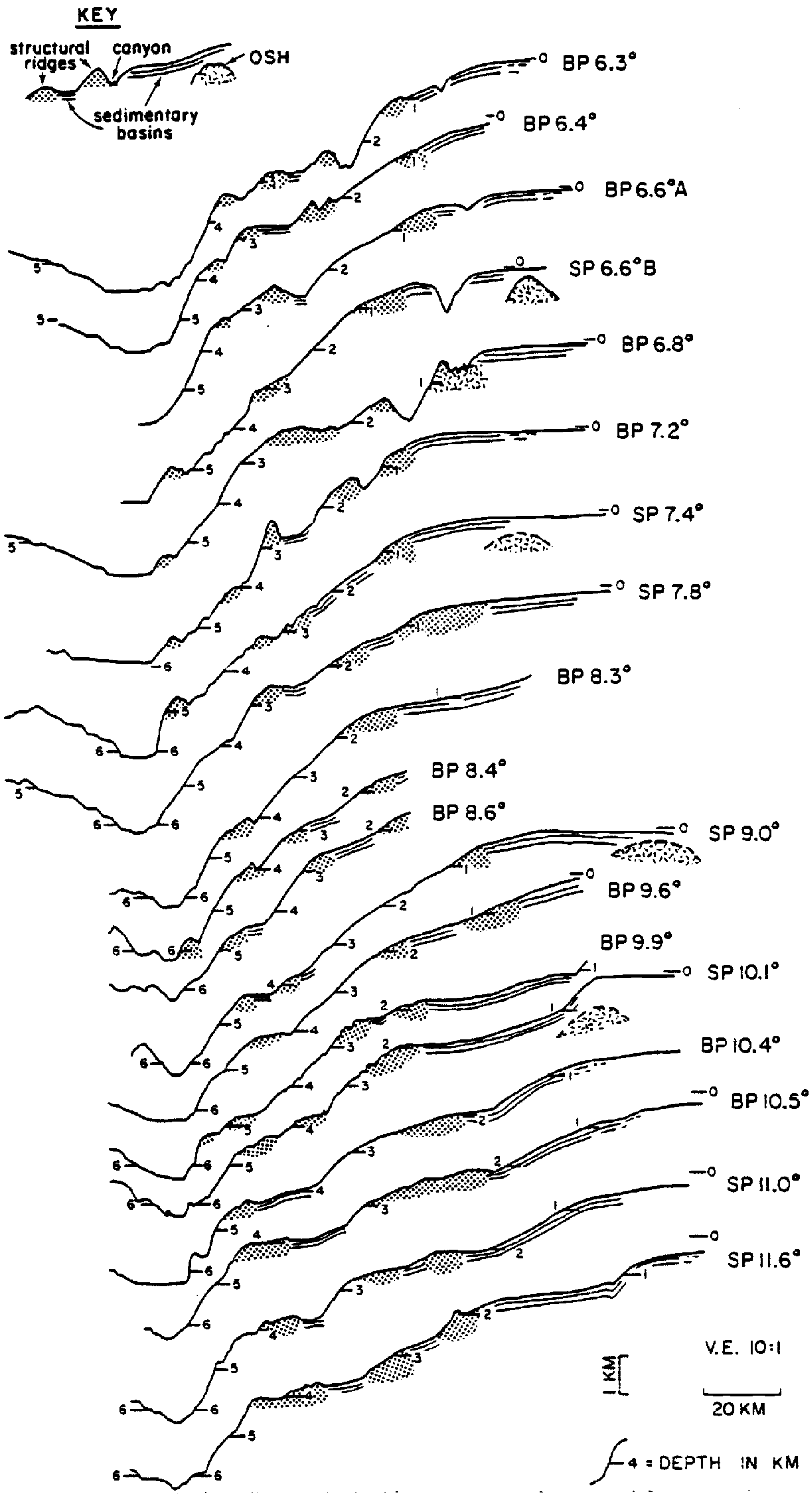


Figure 3A. Bathymetric control used in Figure 2A. See page 13 for caption.

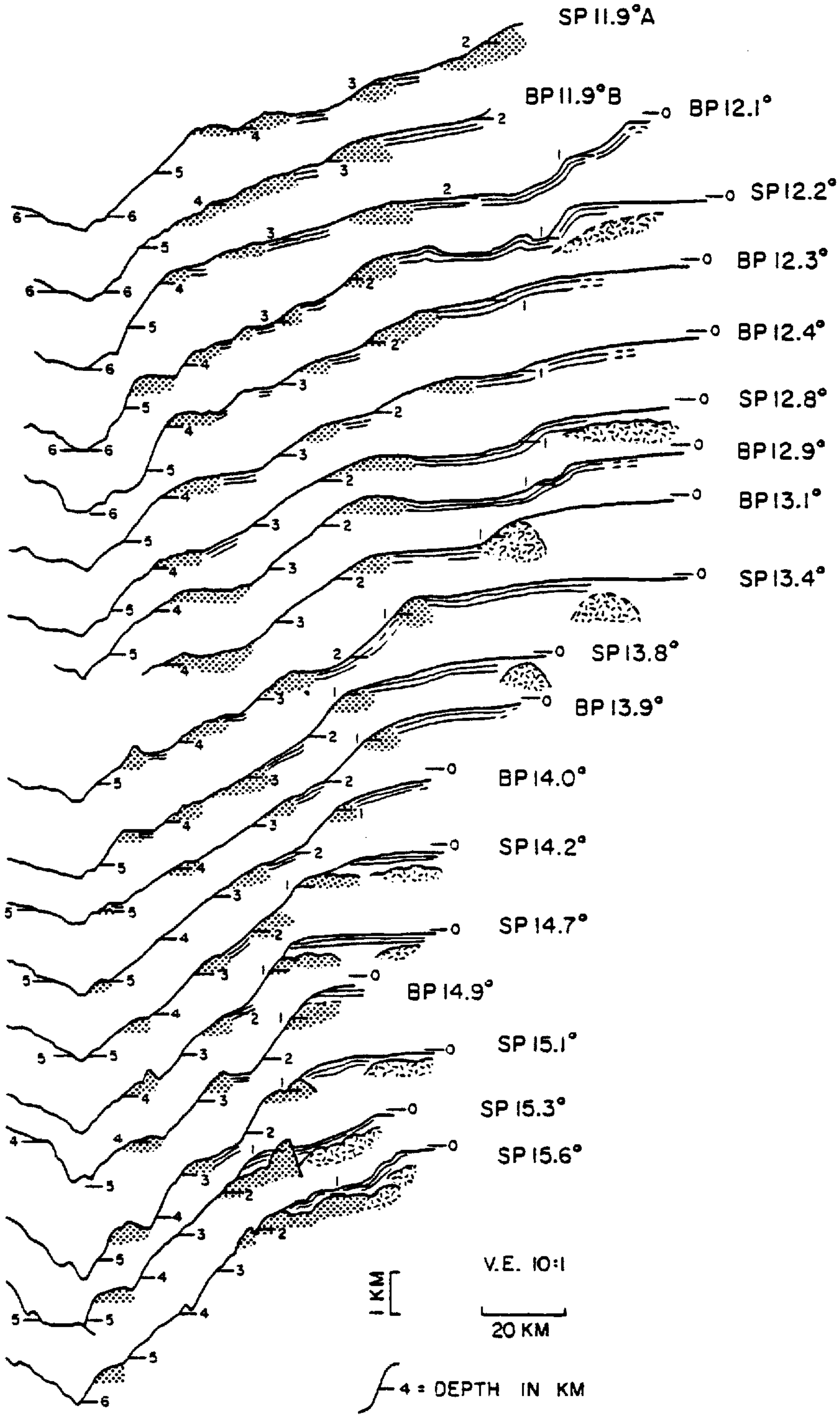


Figure 3B. Bathymetric control used in Figure 2A. See page 13 for caption.

Figure 4. Seismic reflection line drawings across the Peru continental margin, arranged from north to south. Locations are shown in Fig. 2A. OSH is flecked pattern, USR is stippled. Seismic unconformities are shown in heavier line. Selected actual profiles are shown beneath their respective line interpretations. Dredge sites of Kulm and others (1980) are annotated.

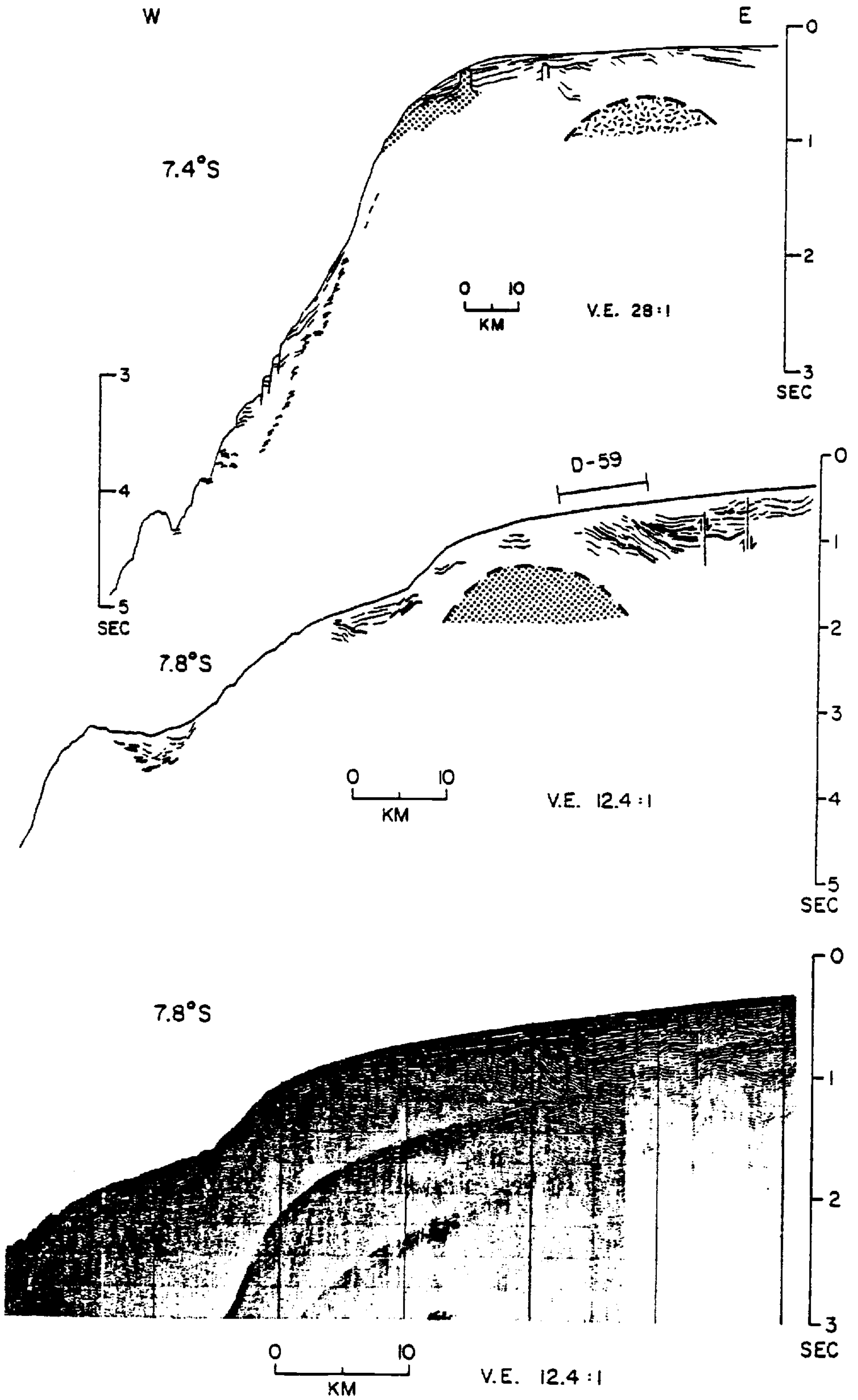


Figure 4A. Seismic reflection line interpretations and actual records across the Trujillo Basin. See page 16 for caption.

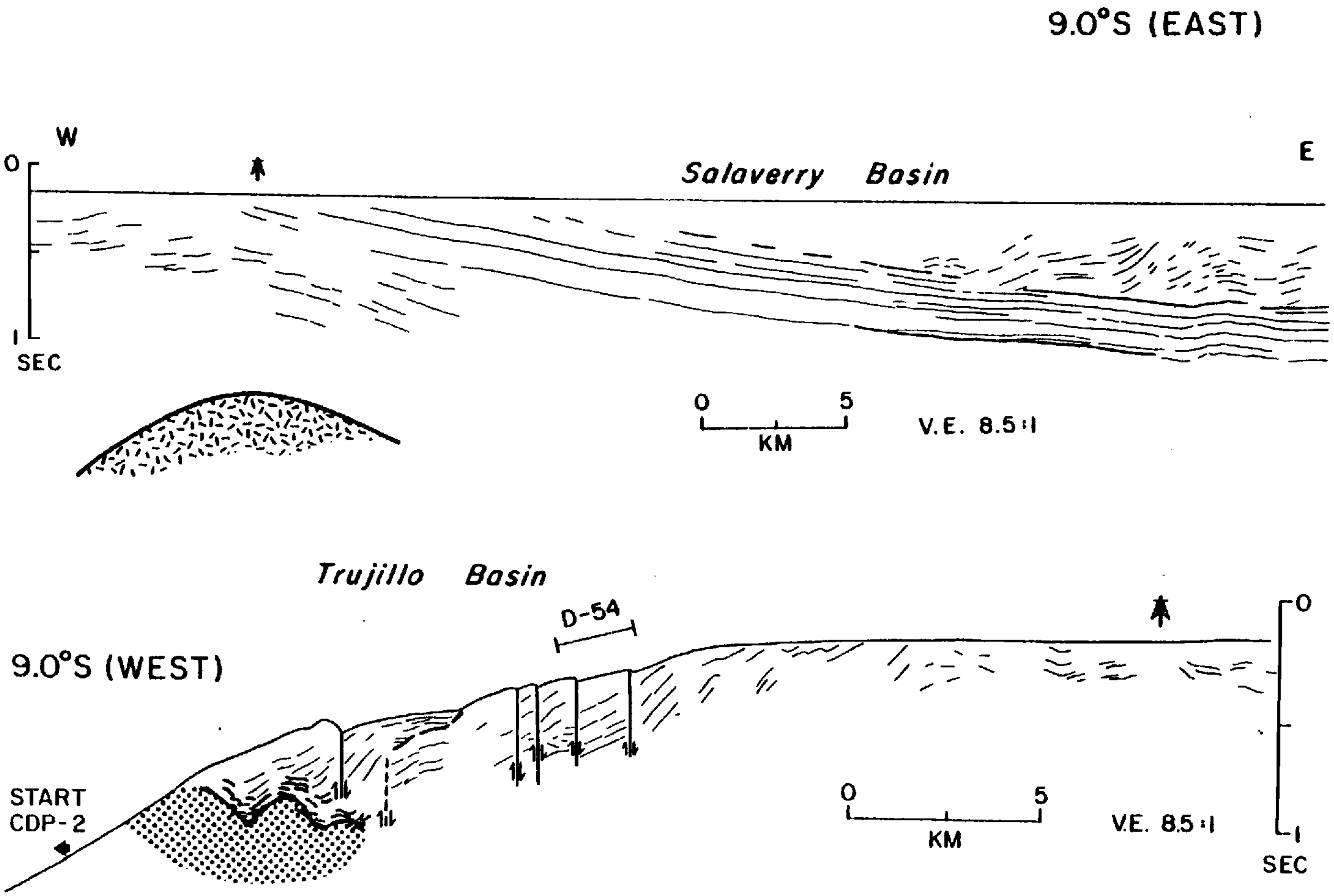


Figure 4B. Seismic reflection line interpretation across the Trujillo and Salaverry Basins. Locations of offshore wells are noted. See page 16 for caption.

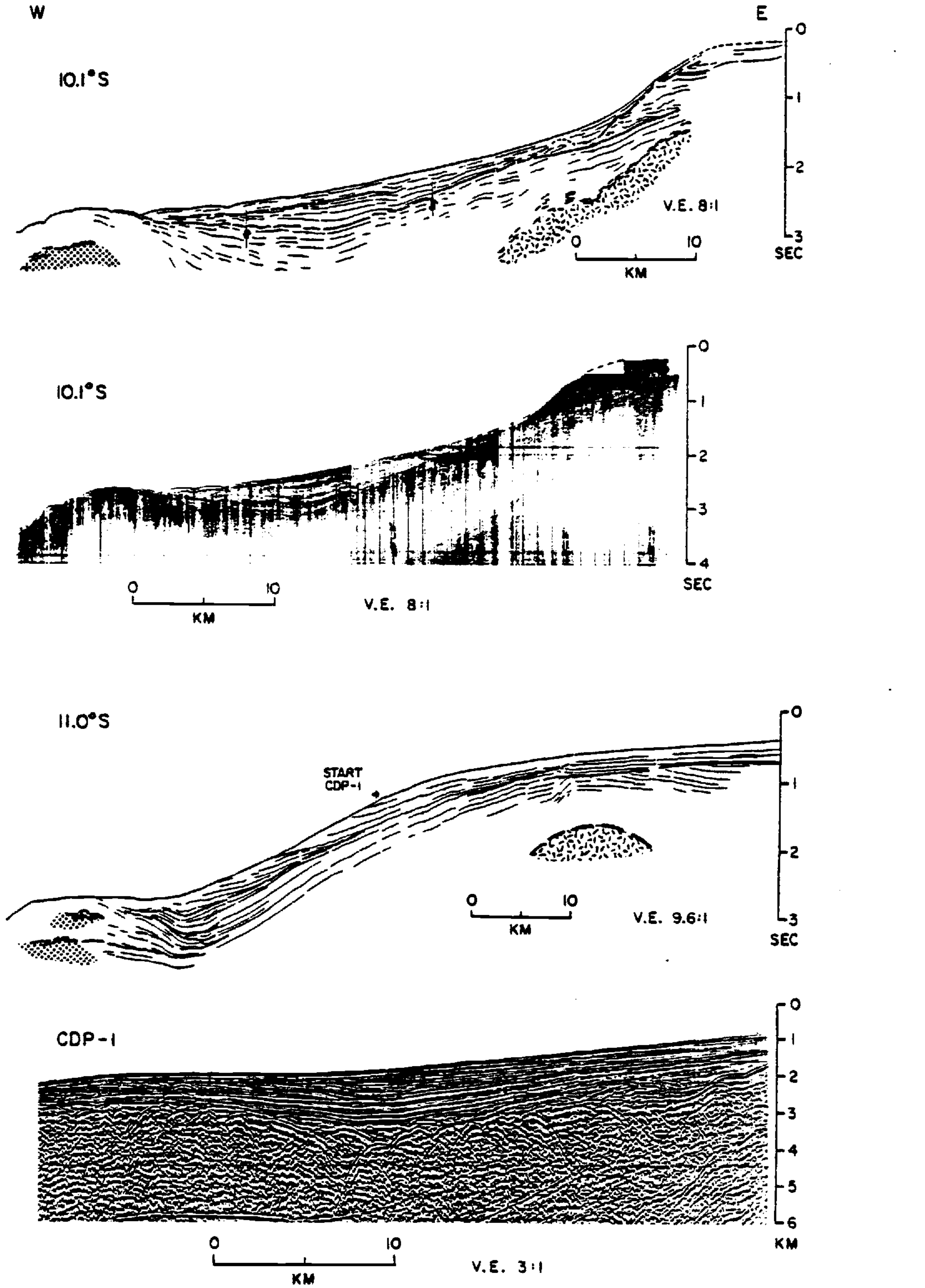


Figure 4C. Seismic reflection line interpretations and actual records across the Lima Basin. Note the good correlation between the single channel record SP-11.0 and the nearly coincident multi-channel record CDP-1 below. See page 16 for caption.

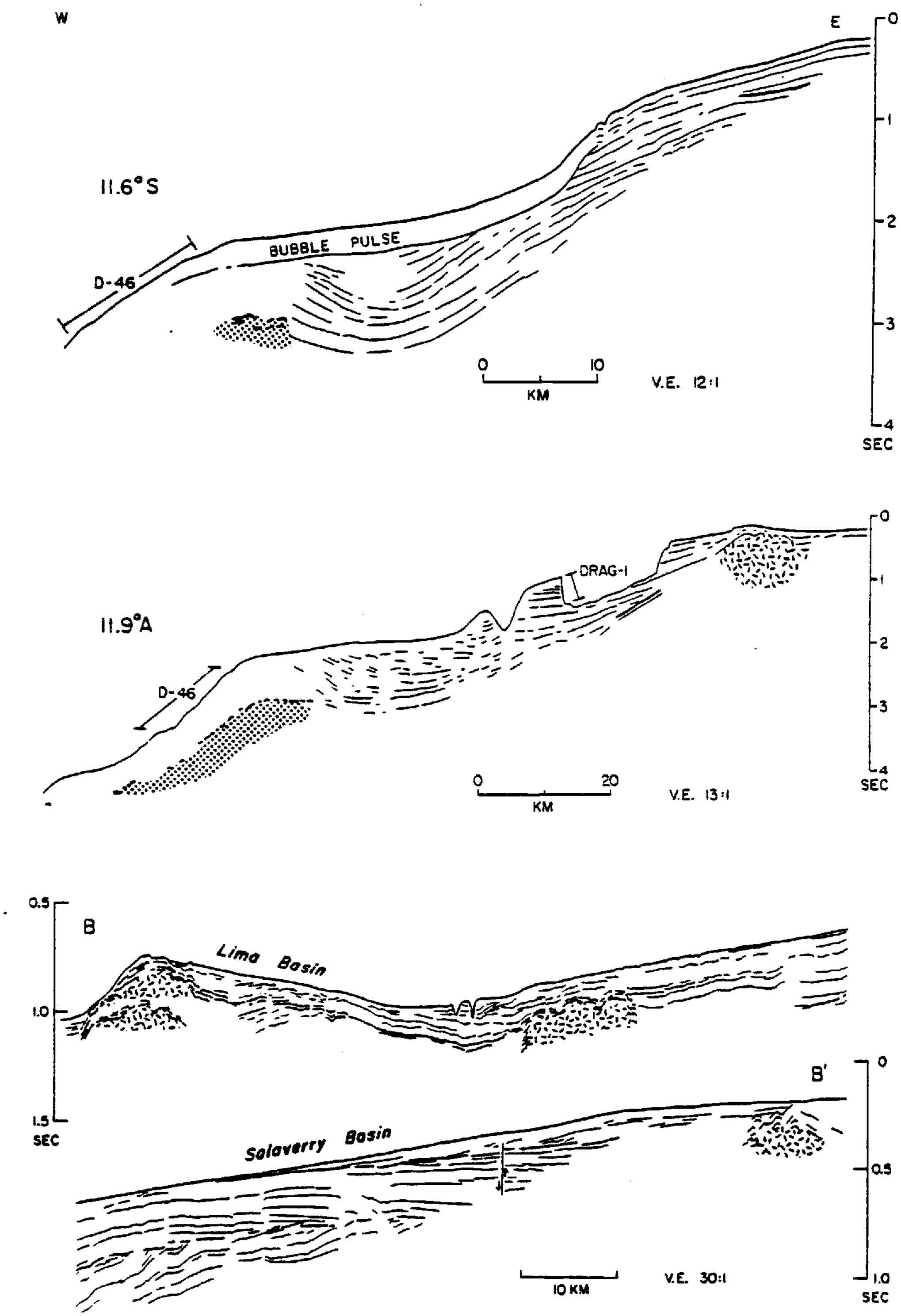


Figure 4D. Seismic reflection line interpretations across the Lima and Salaverry Basins. See page 16 for caption.

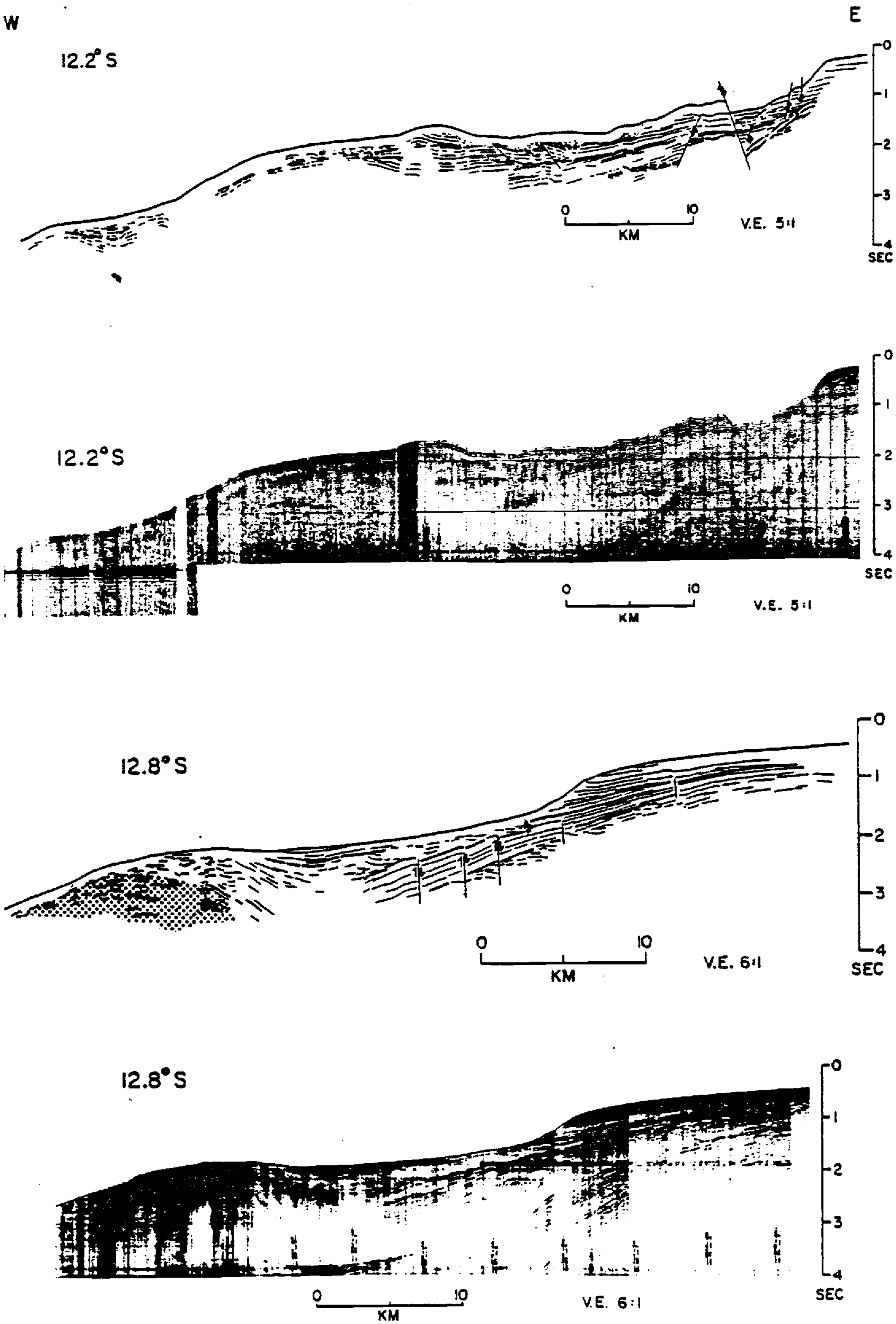


Figure 4E. Seismic reflection line interpretations and actual records across the Lima Basin. See page 16 for caption.

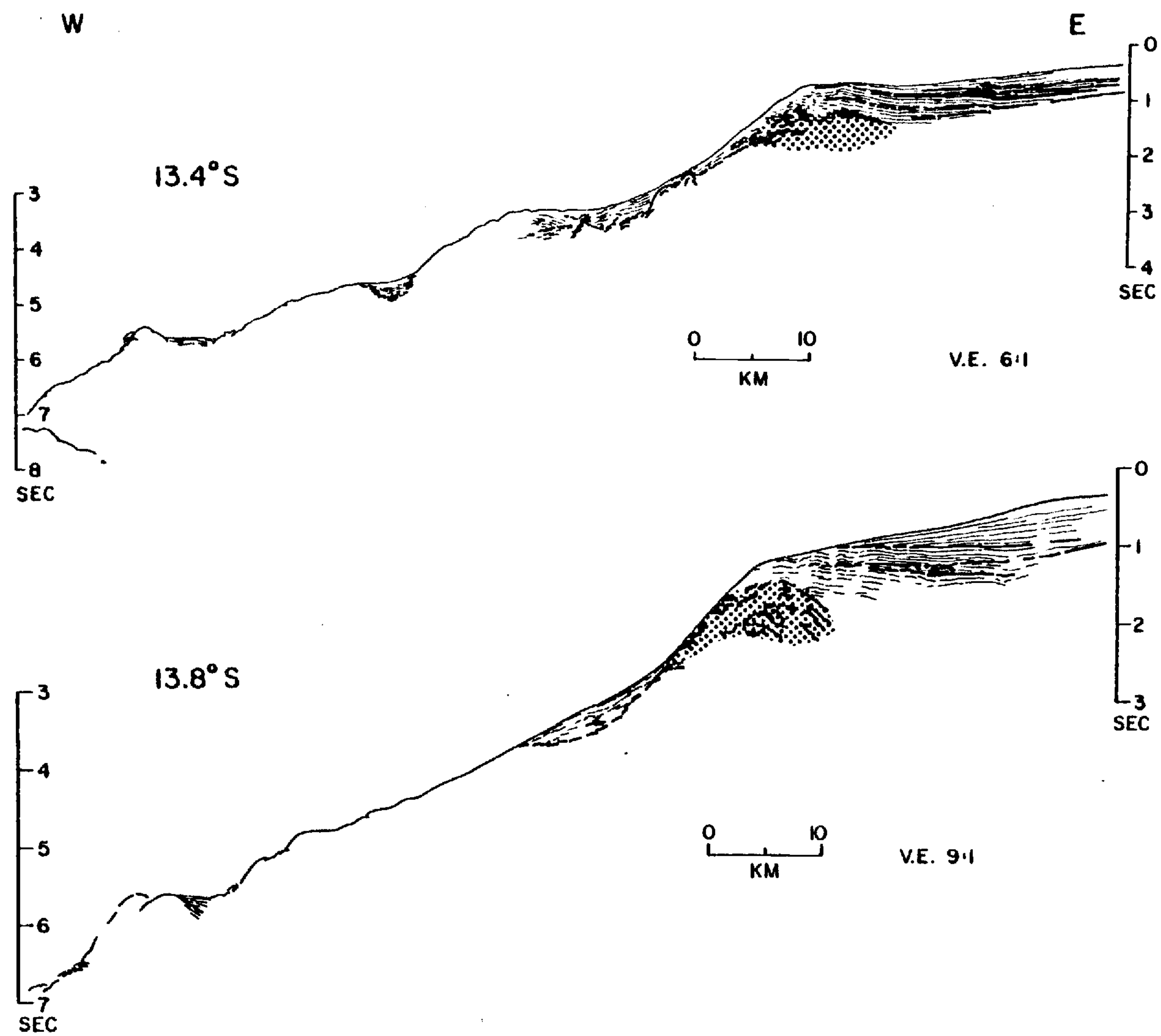


Figure 4F. Seismic reflection line interpretations across the West Pisco Basin. These profiles have been extended shoreward and reproduced in simplified form in Figure 6. See page 16 for caption.

a strongly diffracting anticlinal structure or shoaling acoustic basement (Fig. 3A: SP-6.6B; Figs. 4C,D,E,F: SP-10.1, 11.9A, 12.2, 13.8, line B-B'). In other cases, its presence within the subsurface must be inferred to lie between the gently landward dipping reflectors of the flanking shelf basins and the seaward dipping reflectors of the upper slope basins (Figs. 4A,B,C,F: SP-7.4, 9.0, 11.0, 13.4); in some records, the reflectors overlying the OSH are disturbed or convoluted (SP-7.4, 9.0, 11.0). Similarly, the USR is evidenced by strong diffractions, or transparent zones around which reflectors have been domed, deflected, or pinched-out. Gravity and seismic refraction data provide additional documentation of the OSH and USR (Fig. 5). Drill hole information, the geological terrane of offshore islands, and Travis and others' (1976) account of unpublished seismic records further constrain the mapping of the OSH. Descriptions of the major structures follow, proceeding systematically from north to south along the continental margin, and incorporating the various types of supporting evidence where appropriate (see Fig. 2A).

Shelf Basins and the Outer Shelf High

The Coast Range in northwestern Peru dips below the sea surface at the Negra Point to become the Outer Shelf High (Figs. 2A,B). The offshore projection includes Paleozoic exposures on the islands Lobos de Tierra and Lobos de Afuera before complete submergence occurs south of 7°S latitude (de Almeida and others, 1978). Travis and others (1976) speak of a north-south trend of subsurface basement highs which separates the Sechura and Salaverry Basins. We postulate this trend to be the southern extension of the eastern arm of the onshore Paleozoic outcrops

Figure 5. Geophysical modeling (refraction and gravity) of the Peru continental margin. OSH is flecked pattern, USR is stippled. Horizontal scales for 5A, B, and C are identical; vertical exaggeration of 5C is twice that of 5A and B. A. Gravity profile and resultant crustal density model coincident with seismic reflection profile SP-9.0 across the Trujillo and Salaverry Basins (Figs. 2A, 4B) from Jones (1980). B. Seismic refraction crustal velocity model coincident with gravity model 5A and reflection profile SP-9.0, from Hussong and others (1976). C. Gravity profile and density model coincident with seismic reflection profile SP-13.4 across the East and West Pisco Basins (Figs. 2A, 4F) from Couch and Whitsett (1980). D. Seismic refraction crustal velocity model A-A' across the Salaverry Basin (see Fig. 2A for location) from Hussong and others (1976).

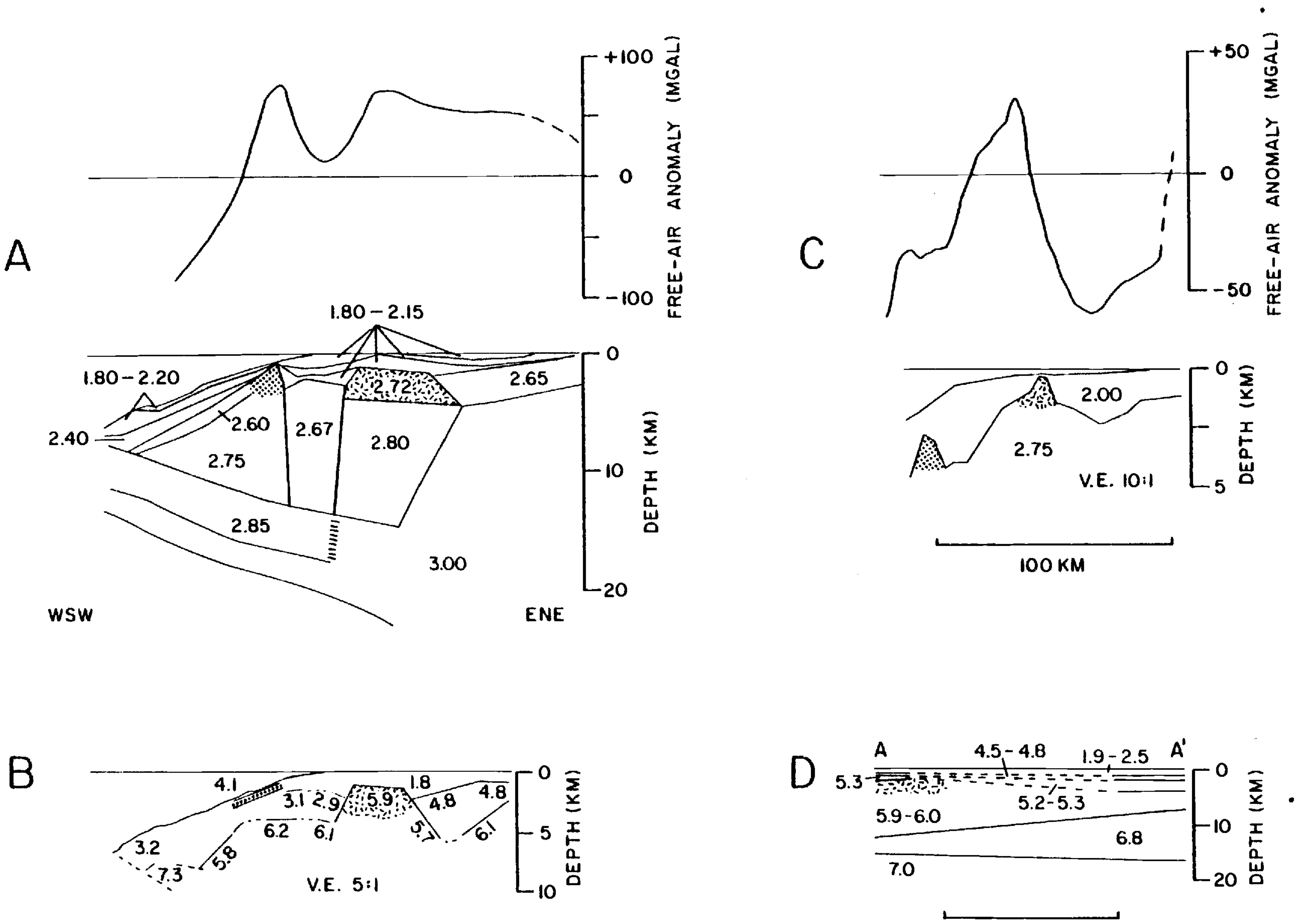


Figure 5. Caption on preceding page.

which circumscribe and delimit the Sechura Basin (Fig. 2B). The structural ridge has been extrapolated from the shoreline near 7°S to a juncture with its western brother in a fork near 8°S. Seismic refraction along the continental shelf verifies a shoaling of the 5.9-6.0 km/sec crustal layer beneath the hypothesized branch of the OSH (line A-A' of Figs. 2A and 5D).

Unpublished drill hole information referred to by Travis and others (1976) near 9°S (Figs. 2A, 4B) describes the penetration of foliated mica schist at a depth of 960 m in the landward well (Delfin), and 2650 m in the seaward well (Bellena). The landward well is positioned over the western limit of long, continuous, gently landward dipping reflectors of the Salaverry Basin, and presumably bottomed in the crest of the OSH. The seaward well drilled a section of discontinuous, disturbed reflectors and penetrated the seaward flank of the OSH beneath the cover of an upper slope basin. Gravity and seismic refraction modeling (Figs. 5A,B; Jones, 1980; Hussong and others, 1976) confirm the presence of a high density, high velocity ridge beneath the landward well. Limited seismic profiling between 9°S and 10°S could not ascertain the OSH and the western boundary of the Salaverry Basin.

Farther south, the Outer Shelf High is again recognized as a shoaling zone of strong reflectors in SP-10.1, at a subsurface depth of about one second (Fig. 4C). In the region beteen 10° and 11.5°S, the OSH seems to largely control the morphologic shelf break, which occurs between 200 and 500 m water depth. Near latitude 11.5°S the OSH extends an eastern proturberance to greet the coastal cape, Point de Salina Ó Lachay, forming the southern boundary of the Salaverry Basin. Features of this area are best seen in the seismic reflection section B-B' which parallels the coastline and rolls over the OSH and its eastern extension several times (Fig. 4D). Between 11.5° and 12°S, a small shelf basin may exist. The western boundary of this basin is defined by Is. Hormigas, an offshore island near 12°S of probable Paleozic terrain (Kulm and others, 1980b; Masias, 1975). Alternatively, the transverse ridge at 11.5°S may merge southward into the Lima Platform, forming a table of shallow acoustic basement across the hypothesized basin. It is unfortunate that the structure of this region could not be resolved among the confounding bottom multiples on the single channel reflection records.

Betweeen 12° and 13°S latitude, seismic reflection profiles reveal a gradual shoaling of acoustic basement from the shelf break to the coastline beneath a thin sedimentary cover of only several hundred meters. The diffracting Outer Shelf High appears to broaden and interfinger with the Mesozoic intrusives and deformed sediments of the Andean foothills, forming a shallow structural platform across the continental shelf. It is referred to as the Lima Platform (Figs. 2A,B). Travis and others (1976) describe a similar acoustic platform offshore of Lima which breaks the continuity of the shelf basins, and free-air gravity anomalies exhibit positive deflections over this part of the shelf (Couch and Whitsett, 1980). Seismic profile SP-12.2 (Fig. 4E) shows the tensional breakdown of this feature beneath the shelf break.

Couch and Whitsett's (1980) free air gravity map reveals a tongue of positive values extending north into the offshore from the Paracas Penninsula, flanked on both sides by closed negative contours. Thus, the OSH is recognized as a ridge of gravity maxima which separates the shelf and upper slope basins (Fig. 5C). The effect of the OSH on the structure of the basinal sediments is readily seen on SP-13.4 and SP-

13.8 (Fig. 6). For this reason we feel that the Pisco Basin, which includes both the shelf and upper slope basins according to Travis and others (1976), should be subdivided into a distinct East Pisco Basin, which lies east of the OSH as a shelf basin, and a West Pisco Basin, which lies west of the OSH as an upper slope basin. In support of this nomenclatural division, the Cenozoic sediments of the opposing basins unconformably onlap their respective sides of the crystalline basement complex in Coast Range outcrops (Travis and others, 1976); the two basins have likely undergone distinct sedimentation histories.

An offshoot of the Outer Shelf High is postulated to extend S-SW from near 13°S latitude marking the southern boundary of the Lima Basin (Figs. 2A,B). This interpretation is somewhat speculative, since the escarpment seen on a single bathymetric profile (Fig. 3B: BP-13.1) is the primary evidence. The interjection of the structural limb seems necessary to account for the rapid change in regional depth between the Lima and West Pisco Basins.

Distribution of Slope Basins, Ridges, and Canyons

Submarine canyons dominate the character of the Peru continental slope north of 7.5°S, where they funnel sediment from upper and middle slope basins directly into the trench (Fig. 2A). All canyons originate seaward of the Outer Shelf High; this crystalline ridge seems to provide an effective barrier against further landward encroachment of their erosive heads. However, a major canyon near 6.8°S has carved into the OSH to some degree; bathymetric profile BP-6.8°S (Fig. 3A) shows the rugged and dissected appearance of this resistant feature. The slope ridges exert a limited control on canyon development and apparently

Figure 6. A series of line interpretations of seismic reflection profiles across the West Pisco Basin, from north to south (see Fig. 2A for locations). Note that, proceeding south, the OSH (flecked pattern) and the USR (stippled pattern) shoal, spread laterally, and finally interfinger to form a shallow, contiguous basement beneath a dramatically thinned and restricted section of overlying sedimentary reflectors. This is possibly a result of impingement of the Nazca Ridge against the continental margin. SP-13.4 and 13.8 are of the same horizontal and vertical scale; SP-14.7 through 15.6 are of the same horizontal and vertical scale; thus, note scale change between SP-13.8 and 14.7. Modified from Johnson and Ness (1980).

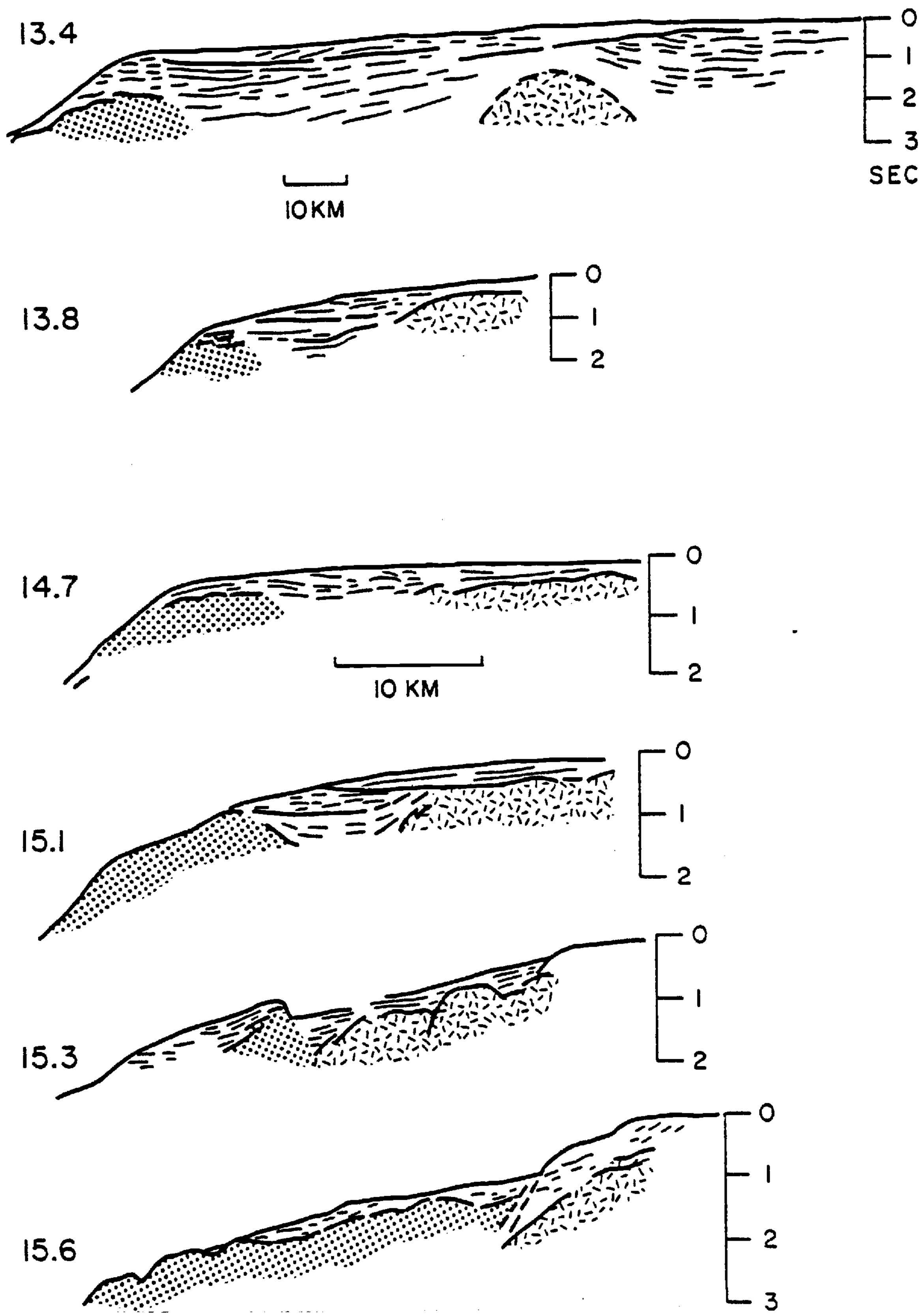


Figure 6. Caption on preceding page.

deflect their downslope progress to some degree; in profile, the canyons are often seen nudged against the landward wall of a prominent ridge (Fig. 3A: BP-6.3, 6.8, 7.2). In many cases, though, the canyons cut directly across the slope ridges, suffering little diversion from a direct gravity-driven path. This is particularly true near the canyon heads, and the extension of the Upper Slope Ridge near 1,000 m is extremely fragmented in this area (Fig. 2B).

South of 7.5°S latitude, canyons are noticeably scarce or absent, and the slope is characterized by extensive upper slope basins lying between the prominent Upper Slope Ridge and Outer Shelf High, of dimensions comparable to the shelf basins. Between 7.2°S and 9.6°S the USR controls the location of the shelf break, which is depressed to 400 to 600 m (Figs. 4A,B: SP-7.4, 7.8, 9.0), and forms the western boundary of the Trujillo Basin (Figs. 2A,B). The basin is at least 300 km long, and approaches 40 km in width. Gravity and refraction modelling clearly indicate the high density, high velocity nature of the USR across SP-9.0 (Fig. 5A,B; Jones, 1980; Hussong and others, 1976).

A basin 150 km long and up to 35 km wide occurs below the Trujillo Basin centered around the 1,000 m contour (Figs. 2A,B); it is named the Yaquina Basin in this study. A 24-channel seismic reflection record across the southern end of this basin (CDP-2 of Kulm and others, 1980b) shows a 2 km thick sedimentary section containing relatively undisturbed reflectors near the center which grade laterally into a highly disturbed and diffracting seismic signature on either side. The disrupted reflectors which surround the undeformed sediments have a domed or anticlinal appearance, and are interpreted to be arms of the Upper Slope Ridge which have diverged to allow the development of the Yaquina Basin between them. Middle slope basins of more restricted dimensions occur commonly between profiles BP-8.4 and BP-9.6 (Fig. 3A). Below 4,000 m along the entire Peru margin, steep gradients (up to 1:6) and rough topography restrict basin development to infrequent and isolated ponds on the lower slope.

From 9.6°S to 13.5°S the upper slope has accumulated a striking trough of sediment which Masias (1975) first identified as the Lima Basin (Figs. 3A,B: bathymetric profiles 9.9 through 13.1; Figs. 4C,D,E: seismic profiles 10.1 through 12.8); it reaches 50 km in width. Acoustic basement is quite apparent in a multi-channel reflection line wich traces SP-11.0 (Fig. 4C, CDP-1), where a subsurface depth of 1.9 seconds is reached at the basin's depocenter. As with the Yaquina Basin to the north, the USR is documented by a zone of structurally disturbed reflectors within the sedimentary sequences. The "submarine canyon" in SP-11.9A is puzzling since it cannot be traced laterally and is contoured as an extremely localized kink on the base map, despite its impressive dimensions (400 m deep and 15 km wide). The continental slope lying seaward of the northern Lima Basin is extremely rugged from 2,000 m to the trench (Fig. 3A; BP-9.9, 10.1); the entire middle slope of this area seems to lack any appreciable sediment accumulation (Fig. 2A). Downslope of the southern Lima Basin, however, middle slope sediments are prolific; the basins are elongate and continuous, apparently traceable for hundreds of kilometers within the presently available profiling density.

Between the southern termination of the Lima Basin and the Paracas Peninsula near 14°S, the upper and middle slope remains covered with a generous blanket of basinal sediments. However, where the OSH surfaces in the Coast Range, and where the Nazca Ridge abuts the margin and causes a dramatic shoaling of the trench, sedimentary basins concurrently become shallower and less extensive (Fig. 2A). This progressive abbreviation of sediment cover is best illustrated by a series of reflection profiles across the West Pisco Basin, the southern counterpart of the upper slope Lima and Trujillo Basins (Fig. 6; modified from Johnson and Ness, 1980). North of 14°S, the basin is comparable in width and depth to the neighboring upper slope basins to the north (Fig. 2A; SP-13.4, 13.8). Ridges of high density material, the OSH and USR, sharply define the basin's lateral boundaries (Fig. 5C; Couch and Whitsett, 1980). Proceeding south, however, the OSH and USR spread laterally as shallow acoustic platforms, squeezing the interlying sediments into a constricted furrow of only 10 km in width by SP-14.7 and 15.1. In SP-15.3 and 15.6, the expanding structural ridges have pinched together into a continuous, though irregular, acoustic basement. Protruding ridges fragment the thin drape of overlying sediment (generally less than 0.5 sec in thickness) into shallow, restricted ponds.

DISCUSSION

Nature of Basement Structures

The preceding descriptive synthesis has emphasized the structural role of the Outer Shelf High and the Upper Slope Ridge antiformal lineaments: that of providing a skeletal framework which molds the geometry and distribution of shelf and upper slope sedimentary basins along the Peru continental margin (Fig. 2B). The composition of the Outer Shelf High may be inferred from the lithologies of the Coast Range: Precambrian and Paleozoic crystalline rocks and metasediments cut by Mesozoic intrusives (Travis and others, 1976). This inference is well substantiated by island exposures (Masias, 1975; de Almeida and others, 1978; Kulm and others, 1980b), drill hole basement lithologies (Kulm and others, 1977), and gravity and refraction modeling showing domes of high density (2.70 to 2.80 g/cc), high velocity (5.9 to 6.0 km/s) material in the subsurface (Fig. 5; Jones, 1980; Couch and Whitsett, 1980; Hussong and others, 1976). In the vicinity of the Lima Platform and the transverse ridge trending offshore from Point de Salinas Ó Lachay (Fig. 2A), this complex is very likely overlain on the east by deformed sediments of the Mesozoic geosyncline and intrusions of the Andean batholith, forming a shallow, contiguous basement across the continental shelf.

Several lines of evidence indicate that deformed basin sediments may constitute the Upper Slope Ridge. The USR's velocity structure is a 4.1 km/s slab within the shallow subsurface, underlain by a puzzling inversion (Fig. 5B). Multichannel seismic reflection profiles across the Yaquina and Lima Basins (CDP-2 of Kulm and others, 1980a; Fig. 4C: CDP-1) reveal that the disrupted anticlinal reflectors that define the USR lie within a sedimentary sequence which overlies a forceful acoustic basement, and that this disturbed seismic facies may be laterally correlative to the relatively undisturbed sedimentary reflectors. Also, the submarine canyons north of 7.5°S dissect the extension of the USR with seemingly little difficulty, compared to the more resistant OSH (Fig. 2A). However, a striking gravity maximum occurs above the Upper Slope Ridge near 9°S, comparable in amplitude to the gravity peak which occurs above the metamorphic OSH at this latitude (Fig. 5A), implying that dense, crystalline material may similarly occupy the core of the USR in some areas. We suspect that the USR is laterally heterogeneous, such that sediments of various ages, deformed during various upper slope orogenies, define its composition.

At 9°S, the USR sits at the very edge of a basement block of 5.8 to 6.2 km/s velocity (Fig. 5B); thus both the Trujillo and Salaverry Basins appear to lie entirely within the continental massif, while the restricted subduction complex of probable deformed sediments begins just seaward of the USR (Kulm and others, 1980a). At 12°S, refraction and multichannel velocity data demonstrate the presence of continental 6.0 km/s velocity crust extending seaward to the Upper Slope Ridge beneath the Lima Basin (Fig. 4C: CDP-1; Fig. 10 of Hussong and others, 1976). Very chaotic sedimentary reflectors overlie a 5.0 km/s block which occurs trenchward of the continental block, and may be fractured or downfaulted continental material.

Stucture and Stratigraphy of Forearc Basins: Tectonic Implications

Current concepts of convergent continental margin morphology stress the importance of the subduction complex: an imbricate stack of offscraped sediment from the descending oceanic plate (Dickinson and Seely, 1979). The subduction complex may develop against the toe of the continental massif; progressive accretion and uplift of this complex then forms the seaward structural limit of the ponded forearc basin (Karig and Sharman, 1975; Karig, 1977). If subduction initiates at some distance from the continental massif, a fragment of oceanic crust may become trapped between the subduction complex and the continental massif, forming the floor and seaward wall of the forearc basin (Dickinson and Seely, 1979). Here again, though, the tectonic underplating of thrust packages to the subduction complex is the active mechanism by which the oceanic remnant is uplifted to cause damming of the forearc sediment. In both models, continental massif will form the landward wall and, at most, part of the landward floor of the forearc basin, interfacing with either oceanic crust or the accreted subduction complex beneath the forearc basin in some, as yet, unknown manner. Variations on subduction complex settings have been applied to numerous continental (and micro-continental) convergent margins about the Pacific, including Alaska (von Huene, 1979), Oregon (Kulm and Fowler, 1974), California (Dickinson and Seely, 1979), Middle America (Karig and others, 1978), northern Chile (Coulbourn and Moberly, 1977), and Sunda (Karig and others, 1979).

Scholl and others (1977) have outlined the main arguments against universally applying the model that tectonically off-scraped material forms the trench-slope break/continental slope of convergent margins. They cite a particular example: the margin of south Chile near 41°S is composed entirely of continental massif, except for the questionable lowermost slope. This is especially true regarding the basement of the forearc sedimentary basins, and is analagous to the situation we find in Peru. From outcrops and drill holes, there can be no doubt that the Outer Shelf High is continental in origin. Although the Upper Slope Ridge is composed of deformed sediments, we believe that it too rests on the continental block, according to refraction and wide-angle reflection velocities across 9° and 12°S (Hussong and others, 1976). Using recent information obtained during the DSDP Japan Trench Transect, Nasu and others (1980) have documented a major forearc basin which lies at greater than 1 km water depth, contains several kilometers of dominantly Neogene sediment, and is floored entirely by seismically determined continental crust.

Like other forearc basins, the shelf and upper slope basins of Peru will deform in response to differential movements of their bounding structural elements (Seely, 1979), in this case the Outer Shelf High and Upper Slope Ridge. Perhaps these more competent (higher density, higher velocity) basement structures serve to transmit stresses resulting from the converging Nazca oceanic and South American continental plates upward into shallower crustal levels, and outward into the less competent basin sediments. Geophysical investigations, rock dredges, drill hole data, and onshore exposures offer important clues with which to decipher the major tectonic movements that affected the sedimentation histories of the Peru shelf (Sechura, Salaverry, East Pisco) and upper slope (Trujillo, Lima, West Pisco) basins.

Shelf Basins - Structure

Extensive normal faulting permeates the subaerial outcrops of the coastal basins (Travis and others, 1976), not unlike the blocky tectonics which have historically characterized Cordilleran movements (Myers, 1975; Cobbing, 1976, 1978). Some blocks have been vertically displaced thousands of meters since the late Cretaceous. Using seismic reflection data, Travis and others (1976) project this structural style onto the continental shelf. Erratic and irregular horst and graben basement features affect the overlying strata in varying degrees. Large-scale gravity induced slumps and slides have also been interpreted on seismic reflection records. An example is seen on SP-9.0 within the Salaverry Basin (Fig. 4B), where folded and fragmented reflectors unconformably overlie continuous and subparallel reflectors, suggestive of soft sediment deformation above a more competent, intact stratal surface.

Shelf Basins - Stratigraphy

With the waning of the lower Tertiary Andean orogeny, the shelf basins subsided and the Cenozoic record of marine sedimentation began, while continental and volcanic deposition prevailed inland. Up to 3,000 m of strata were laid down in the Sechura Basin in post-Eocene time (Fig. 2B; Travis and others, 1976). A major unconformity in land outcrop sections indicates that the geological record of late Miocene, early and middle Pliocene time is missing (Hosmer, 1959); this may correlate inland with pronounced middle/late Miocene tectionism in the Andean belt (Farrar and Noble, 1976).

Geophysical studies across the northern Salaverry Basin show that the sedimentary sequence is often much thinner than 2 km, as defined by a 1.80 to 2.15 g/cc density and 1.8 to 2.5 km/s velocity layer (Figs. 5A,B,D). Below a distinct acoustic interface, several kilometers of 2.65 g/cc density, 4.5 to 5.3 km/s velocity material is present, which we interpret to be deformed sediments of the Mesozoic geosyncline. The sharp velocity and density discontinuity, then, may represent an unconformity which encompassed latest Cretaceous through much or all of Eocene time. The pronounced angular unconformity within less than a half second of penetration in reflection profile B-B' across the southern end of the basin (Figs. 2A, 4D) may correlate with the post-middle Miocene event of the Sechura Basin. Younger reflectors which overlie this unconformity remain subparallel overall, but their individual signatures are jagged and "saw-toothed" in detail, as if bedding interfaces have been disrupted by numerous small-scale offsets. Perhaps a very young (late Neogene) tectonic episode has overprinted the strata in this region.

The East Pisco Basin attains a maximum seismic thickness of 2,500 m (Travis and others, 1976); this interpretation is consistent with gravity modeling over the basin (Fig. 5C). According to coastal outcrops, the sedimentary record begins in the middle Eocene, with interruptions or disturbances following the Eocene, Miocene, and Pliocene (Hosmer, 1959).

Upper Slope Basins - Structure

In the single-channel seismic reflection profile SP-7.4 across the northern end of the Trujillo Basin, fragmented bits of convolute reflection are unconformably overlain by a sequence of continuous, subparallel, undisturbed reflectors (Fig. 4A). This pronounced structural break is tentatively dated as post-Oligocene, by correlation with a disturbance which greatly reduced Miocene deposition in the neighboring upper slope Talara Basin to the north (Hosmer, 1959). In SP-9.0 (Fig. 4B) across the southern end of the Trujillo Basin, chaotic and fragmented reflectors are, by analogy of seismic facies, similarly interpreted to predate the Miocene, including the strata recovered in both drill holes. The overlying Neogene sequence has apparently accumulated in a small sub-basin extending about 15 km landward of the USR, where deeper penetration of reflective surfaces is recorded. These younger strata are cut by a series of high angle reverse faults, upthrown on the seaward side, though reflectors retain a relatively smooth and subparallel expression within the individual fault blocks. Reflectors in the Trujillo Basin across SP-7.8 (Fig. 4A) display a seismic fabric very similar to the young Neogene bundle in SP-9.0, are faulted in a similar manner, and additionally folded. A maximum principle stress centered within the Upper Slope Ridge, including components of both uplift and compression, could produce the deformational features seen in SP-7.8 and 9.0. Such a stress would be oriented roughly normal to the plane of the subduction interface.

In contrast, the young undisturbed sequence which overlies the unconformity in SP-7.4 is inferred to be delta-like progradational deposits from Pleistocene low-stands. If the fragmented reflectors which underlie the unconformity are indeed Paleogene, then the bulk of the Neogene section is missing in this part of the basin. Also, if the undisturbed deposits are indeed Pleistocene, an upper limit could be placed on the deformational episode which affected the Neogene sequences in SP-7.8 and 9.0 to the south. The truncated Paleogene strata which overlie the Outer Shelf High in profiles SP-7.4 and 9.0, and the restricted occurrance of Neogene sediments in the Trujillo Basin, indicate that uplift of the OSH occurred during the post-Oligocene tectonism and perhaps during younger movements as well.

A major structural break occurs near latitude 9.5°S, coincidentally where the Mendana Fracture Zone intersects the margin. Here, the upper slope Trujillo and Lima Basins are offset, as is the trend of the USR (Fig. 2A). The present study could not determine whether a similar offset occurs in the trend of the OSH. Whereas the Trujillo Basin records a history of tectonic activity (folding, faulting, fragmented reflectors), the northern Lima Basin has suffered only minor warpage, appearing as a broad, open syncline of gently dipping strata (Figs. 4C,D: SP-10.1 through 11.9A). The USR appears to have subsided relative to the OSH, evidenced by normal faults of small displacement (SP-10.1) and younger reflectors onlapping strata which have been down-warped seaward around an OSH hingeline (SP-11.0). Paleodepth data from benthic foraminifera of dredged carbonates which were dated by diatoms (dredge locations shown on profile SP-11.9A) substantiate subsidence of 1100 m since approximately 3 to 5 m.y.a. at site D-46, and 500 m since approximately 1 m.y.a. at site DRAG-1 (Kulm and others, 1980b). From the limited age control, we cannot distinguish whether the greater subsidence of the seaward site over the landward site has occurred through a greater subsidence rate over a similar time period, or through a similar subsidence rate over a longer time period. Pinched and upturned strata in the immediate vicinity of the USR, however, may be the result of a mild compressional episode (particularly SP-11.0).

In the southern Lima Basin, subsidence is similarly evident. Normal faults cut the sediment surface where the tensional breakdown of the Lima Platform creates the eastern boundary of this upper slope basin (Fig. 4E: SP-12.2); the locus of youngest sediment accumulation (SP-12.8) has migrated toward the downdropped USR. However, deformational events have complicated the simple syncline which characterizes the reflection profiles of the northern Lima Basin, and tectonism has apparently interrupted the basin's Neogene history of subsidence. Low angle thrusting appears to have fragmented and sheared the seismic depositional sequences of SP-12.2; a series of high angle reverse faults produced multiple offsets in a highly reflective subsurface unit in SP-12.8. As with the Trujillo Basin, simultaneous uplift and compression of the USR could have produced fractures of a near-vertical orientation, upthrown to the seaward side, on SP-12.8; the deformation in SP-12.2 appears to be more strictly compressional. Compression in these upper slope basins may be the surficial expression of vertical or rotational movements of the underlying basement blocks, similar to the deformational style inland (Cobbing, 1978; Myers, 1975).

The West Pisco Basin exhibits a structural history governed by relative stability. Reflectors are subparallel and gently dipping; unconformities are subtle, and downlap indicates progradation from both landward and seaward sources (Fig. 4F, SP-13.4 and 13.8). Alternatively, rotation of onlap around oscillating landward and seaward hinge lines could produce a similar pattern, mimicking bidirectional progradation. In either case, a vertical see-sawing between the Outer Shelf High and Upper Slope Ridge must have affected the strata. Because of the ambiguity between progradational downlap versus tectonically tilted onlap on an active margin, we cannot determine whether subaerial exposure and erosion of the Upper Slope Ridge has ever provided a western source for sediments of the upper slope basins.

Kulm and others (1980b) have dredged sheared dolomicrites of late Miocene to late Pliocene-early Pleistocene age from the Trujillo Basin between 8°S and 9°S latitude, and from the Lima Basin between 11.5°S and 12°S. The matrix lithology is strongly brecciated along subparallel fracture planes and infilled with a microcrystalline cement. Matrix laminae remain subparallel between breccia blocks, denying a sedimentary origin. The oriented brecciation, and granulated grains in thin section point to a compressive origin for these rocks. In one specimen, the matrix breccia was isotopically dated as late Miocene to late Pliocene, while the cement produced a late Pliocene-early Pleistocene age. One could infer that the brecciation occurred during an episode of compression which climaxed the Teritary, with cementation of these fractures occurring contemporaneously, or immediately following in the earliest Quaternary. Thus, many of the compressive structures seen in Neogene sediments on seismic reflection profiles in the Lima and Trujillo Basins were likely culminated in a pulse which closed the Pliocene. In support of this chronology, Hosmer (1959) discusses Pliocene outcrops in the East Pisco Basin which were folded and faulted prior to deposition of Pleistocene detritus or volcanics. More severe tectonism occurred at this time in the far removed foredeep of the eastern Andean foothills.

In the Lima and West Pisco Basins, nearly flat-laying reflectors truncate against scarps of the present sediment surface (Figs. 4C,D,C,F: SP-11.0, 11.6, 11.9A, 12.2, 12.8, 13.4, and 13.8), and scarped interfaces within the shallow subsurface (SP-10.1). Recent removal of hundreds of meters of strata is indicated, since these erosional features are not common within the deeper subsurface. In the West Pisco Basin, the truncated sediments occur directly above the Upper Slope Ridge, against a scarp which initiates a significant increase in slope gradient. Slumps, slides, or debris flows may have caused the erosion of these sediments, possibly evolving into more stratified turbidite sheet flows (submarine canyons are uncommon seaward of the West Pisco Basin) and finally coming to rest in a downslope basin (Underwood and others, 1980). Coulbourn and Moberly (1977) documented similar slumping off the seaward side of an upper slope structural high near 19°S on the southern Peru margin.

In the Lima Basin, the scarps of stratal truncation are separated by a broad plateau from a significant increase in slope gradient (the morphologic expression of the USR). Chaotic gravity flows seem to be an inadequate mechanism of erosion: the seismic facies of these deposits (chaotic reflectors beneath an irregular, discordant surface; see Sangree and Widmier, 1977) are not recognized on the Lima Basin profiles. The sediment would have to be cleanly and completely removed for a distance of several tens of kilometers across gradients of less than 1:50. Lateral erosion and transport via submarine unidirectional currents may be a viable mechanism.

Similar surfaces of erosional truncation were documented in the area of the Walvis shelf in southwest Africa (Van Andel and Calvert, 1971), though much thinner stratal sections were involved (less than 100 m) and water depths were much shallower; bottom currents at 200-600 m water depth were the postulated agents. Current meter data and geostrophic calculations over the Peru margin indicate the presence of a poleward flowing undercurrent whose velocity often reaches 50 cm/s, and infrequently bursts to 70 cm/s (Huyer, 1980; Brink, Allen and Smith, 1979). The core of this undercurrent, however, is centered at a water depth of 100 m, dissipating rapidly below 400 m; it is situated over the upper continental slope. The single-channel reflection records exhibit erosional truncation roughly between 500-1000 m water depth (and down to nearly 2 km in SP-11.0). If the margin's present hydrodynamic circulation is an indication of past conditions, then currents powerful enough to cause significant erosion of the sediment surface should not exist below 400 m. The presence of erosionally truncated reflectors at depths much greater than this implies that a considerable amount of subsidence has occurred in the Lima Basin. Based upon benthic foraminifera within dredged rocks of the upper slope, Kulm and others (1980b) conclude that 500-1100 m of subsidence has occurred in the Lima Basin since the Pliocene/early Pleistocene; reconstruction of this lost elevation would place most of the truncated strata in the water depth range typical of the poleward undercurrent found today. These data supplement the subsidence which is inferred from interpretations of the single-channel reflection records across the Lima Basin. In contrast, foraminiferal studies of the Trujillo Basin show no large scale vertical movements since possibly late Miocene time.

Upper Slope Basins - Stratigraphy

The Talara Basin (Fig. 2B) is the only known coastal basin which contains sediments of latest Cretaceous (Campanian-Maestrichtian), Paleocene, and early and middle Eocene age (Travis and others, 1976); negative relief was sustained in the basin in the midst of pervasive Andean tectonism. However, random and intense vertical, blockly movements (displacements as great as 2 to 3 km) rapidly created and destroyed local sub-basins, and greatly disrupted stratal continuity. Notably, nearly 90% of Peru's petroleum production is from the lower and middle Eocene strata of this basin. The Coast Range prohibits any of these hydrocarbon-rich, early Tertiary sediments from spilling over into the Sechura Basin.

A seismic refraction profile across the Trujillo Basin near 9°S outlines a trough of sedimentary velocity layers approximately four kilometers thick (Fig. 5B). The 2.9 to 3.1 km/sec material in the lower part of the upper slope basin sequence occupies a stratigraphic position correlative to the much higher velocity 4.8 km/s material across the crystalline Outer Shelf High in the flanking Salaverry shelf basin to the east. If the 4.8 km/s layer of the Salaverry Basin is composed of Mesozoic geosynclinal sediments deformed during the early Tertiary orogenic episode, then the corresponding 2.9 to 3.1 km/s velocity layer of the Trujillo Basin should represent either geosynclinal sediments which were affected only slightly by the orogeny, or younger Cenozoic sediments. In fact, deposition in this upper slope basin may have initiated and continued, though with sporadic interruptions, in the midst of the early Tertiary tectonism which occurred inland, comparable to the Talara stratigraphy. It is possible that the Talara and Trujillo Basins were a continuous feature during the early Cenozoic.

A gravity profile which traces the refraction line offers further support for this argument (Fig. 5A). The free-air anomaly remains high over the Salaverry Basin, dropping only about 20 mgal from the +75 mgal maximum situated directly above the OSH. A drop of nearly 70 mgal, however, occurs over the Trujillo Basin. This dramatic negative deflection has been modeled by Jones (1980) as a 2.67 g/cc vertical column of crust extending 13 km into the subsurface, an anomalously low density structure when compared to the 2.75 to 2.80 g/cc crustal blocks which sandwich it and constitute the bulk of the continental margin. It seems more plausible to consider a more surficial effect when modeling the strong gravity minimum, that is, to thicken and deepen the low-density layers of the Trujillo Basin sediments to better conform to the refraction thickness of four kilometers.

By integrating a variety of data sources, the basics of Trujillo stratigraphy may be pieced together in the vicinity of 9°S (Figs. 2A, 7). Proprietary sources and the published data of Travis and others (1976) offer information concerning the basic lithologies penetrated by the drill holes on the outer continental shelf. The seaward well (Delfin) cut 2,650 m of Cenozoic strata: overlying the metamorphic basement (western flank of the OSH) is a sequence of silty, micaceous clay with some calcareous and sandy horizons in the lower section; this is overlain

Figure 7. The general stratigraphy (ages of depositional sequences) of the Trujillo Basin near 9°S latitude. Wavy lines denote unconformities or hiatuses. Inferred from seismic refraction, reflection, drill hole data (industry wells plotted), and correlation with onshore stratigraphy. See text for discussion.

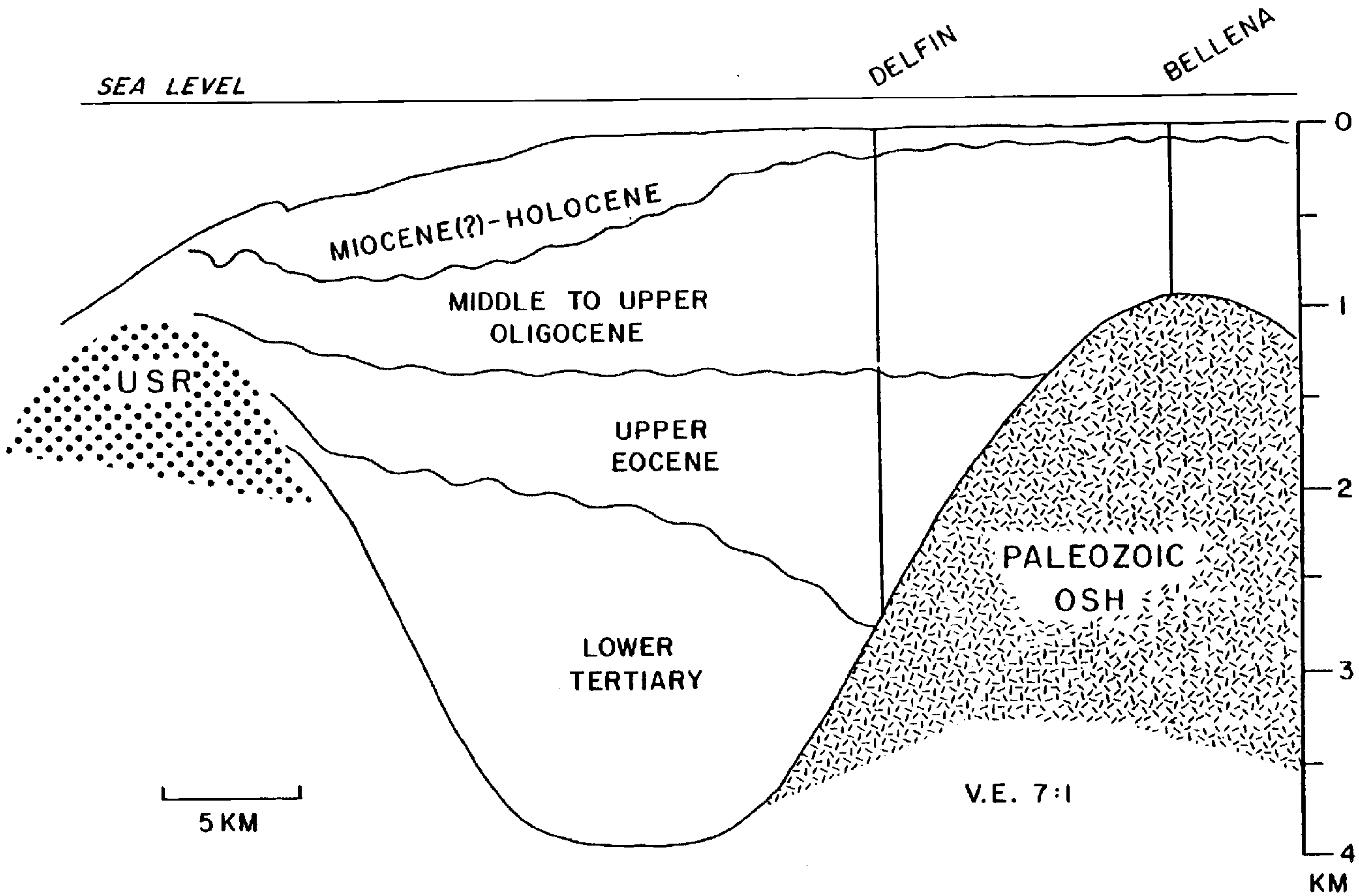


Figure 7. Caption on preceding page.

by a silty clay sequence which contains numerous interbedded turbidites and dolomicrites; a coarse sand unit was the youngest lithology cut. The landward well (Bellena) cut 960 m of silty clay lithologies containing interbedded turbidites and occasional dolomitic limestones before bottoming in the crest of the metamorphic Outer Shelf High; again this sequence is overlain by a coarse sand unit in the top of the hole. Based on lithologic similarity, we correlate the turbiditic, dolomitic strata, which comprises the entire sequence of the landward well, with the upper section of the seaward well.

As discussed earlier, we interpret the lower 2 km of Trujillo Basin sediments to be early Tertiary in age as evidenced by a 2.9 to 3.1 km/s velocity refraction layer (Fig. 5B). Travis and others (1976) note that the stratigraphic succession penentrated by the offshore wells begins in the upper Eocene; we believe this is true for the seaward well only. A post-Eocene unconformity is extrapolated from onshore sequences exposed in the Talara Basin (Hosmer, 1959). Hosmer's (1959) paleogeographic reconstruction of middle to late Oligocene time shows Pacific drainage of the eastern Andean forelands through an outlet in northwestern Peru; this outlet was closed by tectonism in Miocene time, and freshly eroded Andean detritus was flushed eastward through the newly formed Amazon drainage. Thus, we interpret the turbidite sequences of both drill holes to be derived from this northern provenance (northwest Peru) and to be of middle to late Oligocene age, with implications that a continuous Talara-Trujillo Basin may have existed at this time. The upper-most coarse sands in the drill holes of the eastern Trujillo Basin may record the early Miocene movements which caused unconformities in coastal outcrops at the close of the Oligocene (Hosmer, 1959). Younger Neogene strata are likely confined to the upper few hundred meters of section in the east, but thicken to approximately 500 m in the western Trujillo Basin, as indicated in seismic reflection profile SP-9.0 by the deeper penetration of relatively undeformed (though offset by faults) reflectors which presumably post-date the early Miocene deformation. The oldest dated rocks dredged from this part of the basin (D-54 of SP-9.0; Kulm and others, 1980b) give isotopic and paleontologic ages which are not refined closer than an inclusive late Miocene through late Pliocene bracket.

The filling of the Trujillo Basin, then, was nearly complete by the close of the Oligocene, at which time pronounced uplift must have occurred, and Neogene strata are limited to a small pond in the western part of the basin (Fig. 7). The Outer Shelf High apparently acted as a positive, isolating element throughout much of the basin's evolution, though subsidence of this feature during middle and late Oligocene time allowed nearly a kilometer of sediment to accumulate at its crest. The Oligocene strata which overlie the OSH have been truncated by post-Oligocene uplift of this feature; if Neogene deposition ever extended farther eastward, it has also been stripped by subsequent uplift of the Outer Shelf High. If the Upper Slope Ridge is a deformed and indurated lateral correlative of the Tertiary basinal sediments, then it need not have provided a structural limit to the basin's western boundary until the early Miocene deformation, after which younger sediments onlap the USR (SP-9.0, Fig. 4B).

A multichannel reflection line across the Lima Basin at 11.0°S reveals a vivid acoustic basement at a subsurface depth of approximately 2 km (Fig. 4C: CDP-1). Comparison with a refraction profile along 12°S

(Hussong and others, 1976) indicates that crystalline continental massif may floor these sediments and cause the sharp velocity contrast, since a 2.4 km/s versus a 6.0 km/s interface occurs near this depth. Kulm and others (1980b) have dredged late Miocene to Holocene rocks from this part of the Lima Basin, and conclude that deposits of this age account for at least the upper 1.3 km of the stratigraphic section, when sample locations were projected onto reflection profiles. It follows, then, that Paleogene strata are at most restricted to the several hundred meters of unsampled basal section, or may be completely absent. The Lima section provides a sharp contrast to the Trujillo Basin statigraphy, where nearly 4 km of pre-Miocene strata constitute the bulk of the sediment pile. Thus, early Miocene tectonism uplifted the predominantly Paleogene Trujillo Basin causing a near fatal reduction of sediment accumulation, followed by late Miocene subsidence of the Lima Basin and inception of the predominantly Neogene accumulation. It is noteworthy that the Mendana Fracture Zone presently marks the boundary and offset between these two upper slope basins with their contrasting structures and strata, perhaps signifying its influence as a lithospheric tear which has caused segmented subduction since Miocene time.

Little is known concerning the stratigraphy of the West Pisco Basin. From coastal outcrops and seismic profiling, Travis and others (1976) project 3000 m of upper Eocene and younger strata into the offshore sequence. In the northern, undisturbed part of the basin, gravity modeling (Fig. 5C) agrees with a similar basinal thickness.

Forearc Basin Tectonics

Available geological and geophysical evidence indicates that the major Peru forearc basins of the shelf and upper slope are floored entirely by continental crust, while sinuous basins of more stunted dimensions occupy the restricted subduction complex trenchward (Hussong and others, 1976; Kulm and others, 1980a; Kulm and others, 1980c). The Upper Slope Ridge and upper slope basins, being at the very toe of the continental massif, may be more susceptible to Nazca-South America plate interactions, and more responsive to changes in these interactions over time, compared to the Outer Shelf High and shelf basins which occupy a more stable interior position. We speculate that in the specific case of Peru upper slope basins, periods of uplift and compression represent pulses of intensified plate convergence, while periods of subsidence and tension represent quiescent plate activity. This statement cannot be defended without additional drill hole control, but it seems more applicable in Peru than in forearc basins which lie in part, or in full, on subduction complexes, since these features can simultaneously exhibit uplift and subsidence on different sides of the trench-slope break, and can be created or destroyed in tens of millions of years (Karig and Sharman, 1975; Seely and others, 1974).

Dating unconformities and deformational episodes in upper slope basins, then, may give a more direct indication of plate movement than dating inland magmatic/tectonic activity, in which a time lag of several million years could exist. In fact, historical evidence would indicate that antithetic tectonic regimes may exist simultaneously in the upper slope region vs. the inland cordillera. For example, the western volcanic geanticline occupied the toe of the Cretaceous continent while geosynclinal conditions persisted inland (see Geologic History for references). During the early Tertiary uplift and orogeny which terminated the geosyncline, deposition occurred in the upper slope Talara and possibly Trujillo Basins. Post-Oligocene uplift and deformation of the Talara and Trujillo Basins did not manifest itself inland until the late Miocene, concurrent with Lima Basin subsidence. Unconformities and deformational episodes in shelf basins seem to predominantly reflect tectonism in the magmatic arc, though they are caught in an intermediary position.

CONCLUSIONS

1. Structural basement ridges subparallel to the onshore Andean trends control the distribution of forearc sedimentary basins. In general, a series of shelf basins (Sechura, Salaverry, East Pisco) is confined between the western Andes and the Coast Range/Outer Shelf High (OSH); a series of upper slope basins (Trujillo, Lima, West Pisco) is cradled between the Coast Range/OSH and a prominent Upper Slope Ridge (USR).
2. The OSH is composed of Precambrian and Paleozoic crystalline rocks and metasediments cut by Mesozoic intrusives. Deformed Mesozoic sedimentary rocks probably onlap the eastern flank of the OSH and may also constitute effective basement for the overlying Tertiary sediments of the shelf basins. The USR is composed of deformed sediments which appear to be lateral correlatives of the relatively undisturbed sediments which lie within the upper slope basins. Both shelf and upper slope basins are floored by the continental massif; the subduction complex apparently lies seaward of the USR.
3. A major change in the structure of the upper slope basins occurs near 9.5°S. North of this latitude, seismic reflectors are frag-

mented, folded, and cut by high angle reverse faults, indicating a basinal response to compression and uplift of the Upper Slope Ridge. South of this latitude reflectors are smooth and continuous, and form a broad syncline indicative of mild, quiet subsidence, though deformational structures overprint this pattern farther south.

4. A major reorganization of the structure and sedimentation of the Peru continental margin apparently occurred in early Neogene time. North of 9.5°S, in the upper slope Trujillo Basin, several kilometers of sediments which had accumulated in Paleogene time (a section nearly 4 km thick at 9°S) were uplifted and deformed immediately following the Oligocene, and subsequent sedimentation is of greatly reduced thickness. South of 9.5°S in the upper slope Lima Basin, the bulk of the stratigraphic section (2 km thick near 11.5°S) seems to be of late Miocene age or younger; the middle/late Miocene initiated subsidence and sediment accumulation on this part of the upper slope, coincident inland with a period of intense Andean orogeny. Pronounced unconformities reflect these Miocene movements in the shelf basins. A final episode of upper slope deformation closed the Pliocene, and affected the shelf basins to a lesser degree.

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