GEOPHYSICAL DATA AND THE NAZCA-SOUTH AMERICAN SUBDUCTION ZONE KINEMATICS: PERU-NORTH CHILE SEGMENT

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Abstract. Results from deep seismic sounding show that the continent-ocean transition zone structure is highly complex along the western boundary of the South American Plate. The main results are: i) 5.0-5.4, 6.0-6.3, 7.0-7.3, and 7.9-8.3 km/sec refractors under the deep ocean, ii) the average dip of the crust-upper mantle transition is about 6° towards the continent, iii) on the continental shelf off-central Peru the refractor velocity families are: 5.1-5.3, 6.0-6.2, 6.8, 7.3 km/sec for the material below the sediment cover. Off-southern Peru, models satisfying travel times and wave forms show an upper crust with velocity increasing with depth from about 6.0 to 6.3 km/sec, a lower crust with velocity about 6.9 km/sec and a velocity inversion immediately above the Mohorovicic discontinuity.

A regional gravitational anomaly map, reduced to sea level datum, shows great amplitude anomalies associated with regional tectonic, geologic and morphologic elements. The Nazca ridge, on the other hand, has no gravitational signature, i.e., it is isostatically compensated, but the electrical conductivity data shows a significant anomaly on its extension under the continent.

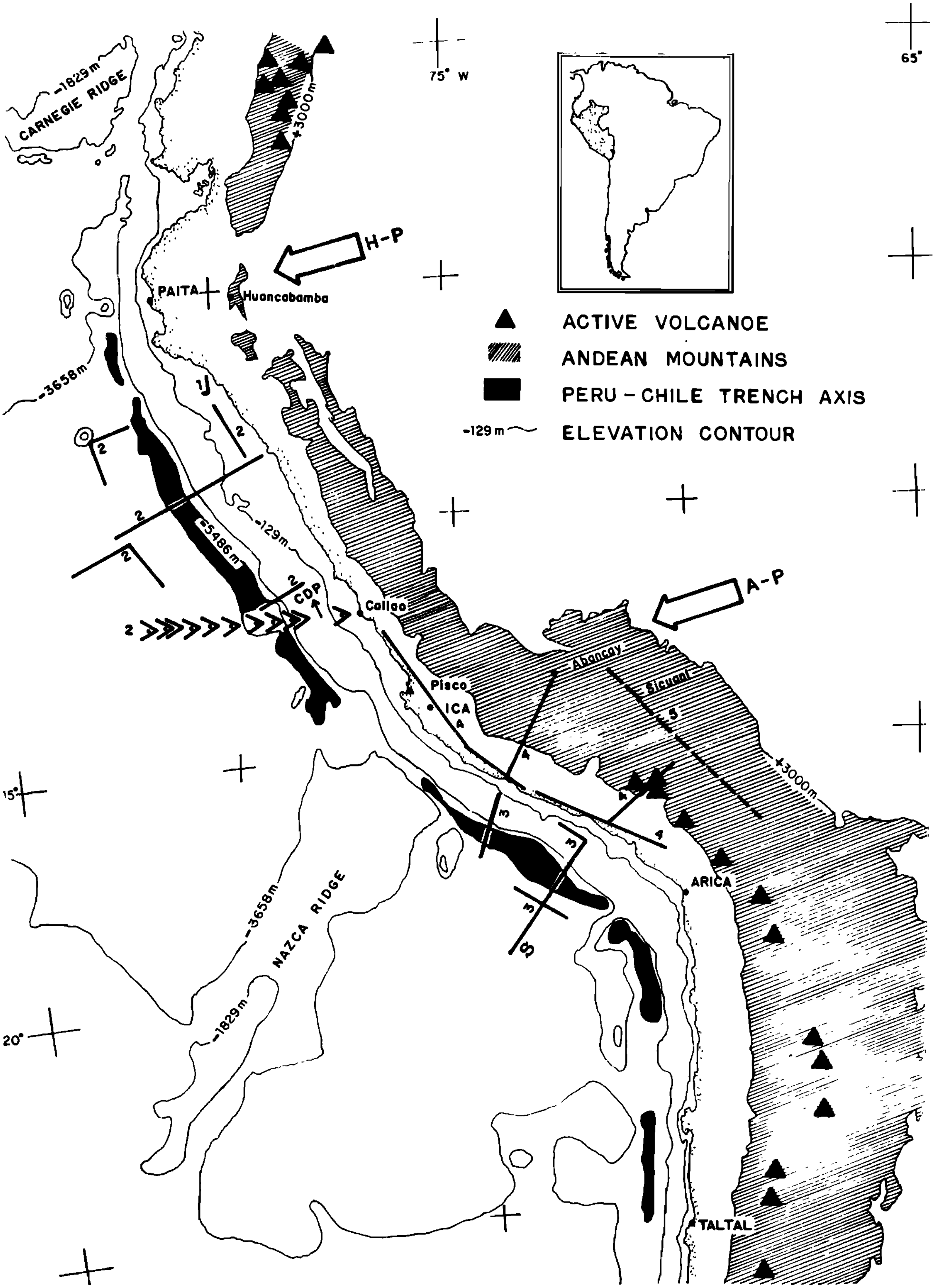
From the integration of seismicity, geochronology, geochemical, geologic and tectonic data, a model for the Andean subduction zone is proposed. This model considers the coexistence of two normal dipping Benioff zones, i.e., dipping 30° for central Peru, and one normal Benioff zone for southern Peru-north Chile. The western zone is a young relatively shallow belt, presently developing, and it is associated with the Peru trench in central Peru. The eastern zone is an old relatively deep Benioff zone, and it is in process of extinction. This zone is, approximately, along the Subandean zone. Both zones are connected through a low dip, seismically active detachment zone. The episodic nature of intrusive implacements is related to periods of re-activation of South Mid Atlantic ridge and to the vertical migration of magmatic blobs into the South American Plate upper-mantle and crust. The final stages of this emplacement are assumed to be guided by pre-existing structures, so that great bulges on the earth surface will not be produced. Taking into account the geochronological data for the Pucallpa alkalic complex. the approximate date of the third active spreading episode of the South Mid Atlantic spreading center, and the average westwards velocity of displacement of the South American Plate, 4.4 cm/yr ascent velocity is calculated for a 5-km radius spherical blob moving up in a medium with 5×10^{20} poise of viscosity for 300 km path.

Introduction

Knowledge of subduction zone kinematics is of most importance in understanding Earth's dynamics and causal processes. A great deal of effort by earth scientists has been devoted to this end. At present, a wealth of data have been gathered and interpreted, as a result, a great number of models has been proposed to explain observed facts or inferred material properties or processes taking place deep on earth.

Processes of prime importance on the earth's history are those that take place in zones of plate convergence, in particular, in zones like the Andean one which was thought to be a typical paradigm, in the early years of plate tectonic theory. However, as more and better data is collected, proposed models differ from the typical ones.

In the first part of this paper, geophysical data on material properties, and dynamics of the Nazca-South American plate


ACTIVE VOLCANOE
ANDEAN MOUNTAINS
PERU - CHILE TRENCH AXIS
-129 m ELEVATION CONTOUR
75° W
65°
15°
20°
CARNEGIE RIDGE
-1829 m
+3000 m
H-P
A-P
PAITA
Huancabamba
-3658 m
-5486 m
-129 m
CDP
Callao
Pisco
ICA
Abancay
Sicuani
ARICA
NAZCA RIDGE
-1829 m
TALTAL

subduction zone: Peru segment, for the period 1973-1979, are briefly reviewed. A similar review can be found in Woollard and Ocola (1973), for years before 1973. In the second one, models that explain geologic and tectonic gross features, and seismicity are proposed. The models take also into account, geochemical data, the westward displacement of South American plate, the great linear features of regional tectonic and geologic elements ; and attempt to explain present seismicity morphology, volcanic activity distribution and other tectonic manifestations such as the great elevation and bulk of the south Peru Andes (including the Peru-Bolivia altiplano), marine terraces, etc.

Deep Seismic Sounding

During the last decade, the controlled source seismology community has maintained a great interest in determining material properties and structure of the crust and upper mantle in the ocean-continent transition zone and neighbouring areas along the western margin of the South American plate.

In 1976, a multinational seismic refraction experiment was carried out with participation of U.S.A. universities of Wisconsin, Texas and Washington, Carnegie Institution of Washington, and Instituto Geofísico del Perú. The lay out of the experiment is shown in Fig. 1, lines 3s and 4s.

TABLE 1. 1976 Multinational Controlled - Source Seismic Experiment Shot Point Location.

Place	Latitude °S	Longitude °W	Comments
Atico	16.42	73.70	Shot placed in the ocean.
Cuajone	17.04	70.70	Open pit copper mine.
Marcona	15.19	75.13	Open pit iron mine.
Toquepala	17.24	70.61	Open pit copper mine.

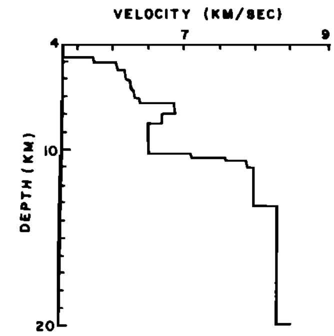


Fig. 2. Velocity-depth function for deep ocean west of the Peru trench axis which matches travel times and wave forms derived by the construction of synthetic seismograms assuming a plane layer medium. The velocity for the low velocity zone was set to 6.5 km/sec (after Meeder et al., 1977).

In the first part of the experiment seismic data for several profiles were gathered between Lima (12°S latitude) and the Peru-Chile border from four shot points: three on land, one in the ocean. The location of these points are given in Table 1. The analysis and interpretation of results have not been published yet.

In the second part, two on-shore and off-shore profiles were obtained. The land stations were set along profiles normal to the Andes. Besides these two lines, several lines parallel to the trench axis were fired and data were recorded on ocean bottom seismometers (OBS).

Meeder et al. (1977) discussed results from profiles fired on the deep-ocean side of the trench. They derived several models using different methods of interpretation of seismograms assembled in 'record sections'. In general, the models

Fig. 1. Location of controlled source seismic studies reviewed in this paper, and major tectonic and morphologic elements in western South American subduction zone. The seismic lines are labelled according to (1976) profiles: Solid lines are standard modalities of seismic refraction profiles. > simbols due west off-Callao indicate ASPER stations. CDP: Common-depth-point digital seismic line; 3) Oceanic profiles of 1976 multinational experiment (Meeder et al., 1977). Crustal models described in this paper correspond to the southernmost line (S); 4) Continental profiles along- and across-strike of the Andes mountains from shots on land and in the ocean (Aldrich et al., 1976), Table 1; 5) Peru-Bolivia altiplano seismic refraction profile (Ocola et al., 1971). A-P: Abancay-Pisco deflection, H-P : Huancabamba-Paita deflection. Note that the active volcanoes (solid triangles) are outside of the segment bounded by the two deflections.

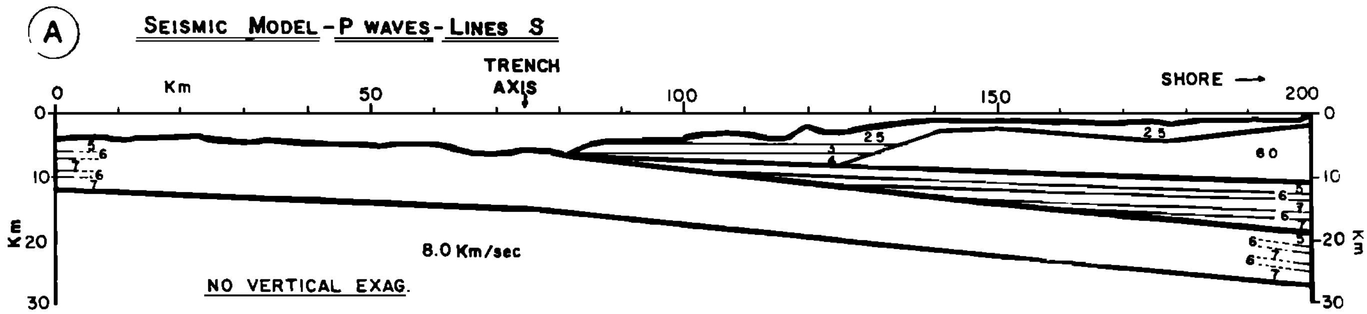


Fig. 3A. Seismic model of Peru trench subduction zone between the shelf and OBS stations. Outlined by heavier lines are oceanic crust and upper mantle, sediment wedge of the continental slope along with sediment basin on the continental shelf, higher velocity material underlying the continental shelf, and a triangular region with crustal crystaline rock velocities. This last region is shown schematically as a thrust of oceanic crust, but could also be continental material (after Keller et al., 1978).

show a monotonically increasing velocity depth function with a low velocity zone in the lower crust. A model, using theoretical travel time computation and synthetic seismogram that closely matched the observed travel time and wave forms of 50-km profile normal to the trench axis is shown in Fig. 2. The main features of this model are the velocity inversions between 8- and 10-km depth, the 7.9 km/sec velocity at Moho discontinuity.

Keller et al. (1978) modeled the deep structure of the shelf and continental slope, southernmost line (S), Fig. 3A. The model was constrained to satisfy reversed travel times between the shelf and deep ocean OBS, near vertical reflection times, and gravity anomaly data. The important features of the model are the thin low velocity layers in two of the deepest three refractors under the continental shelf, the 'low velocity material of the continental slope', and dip about 6° towards the continent, of the oceanic Moho under the continental shelf.

In 1976, Hussong et al. published a composite crustal section for the ocean-continent transition zone between 8° and 12°S latitude, lines marked with 2 in Fig. 1. According to the Hussong et al. (1976), data from five standard two-ship reversed refraction lines, eleven overlapping split profiles along a 375-km line extending from the shelf to deep ocean across the trench, twelve airgun sonobuoy precision recorder (ASPER) stations distributed on line, were used. The deep crustal structure was obtained from a 190 km long reverse profile parallel to the coastal line, and shot on the flat part of the continental shelf between 8° and 10°S latitude. The refraction data was suplemented by a commercial multichannel, common-depth point (CDP) digital reflection seismic line on the continental slope.

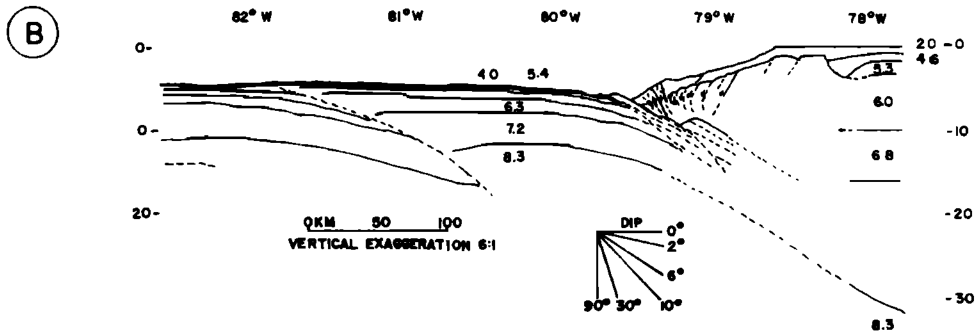


Fig. 3B. Composite crustal cross-section of Peru trench including the major tectonic features identified from seismic data between 8° and 12°S latitude (after Hussong et al., 1976). Note the underthrust fault at about 250-km west from the Peru trench axis.

TABLE 2. Compressional Wave Velocity Depth Section in the Off-Shore Part of Sechura Basin (6.9°S, 80.4°W) (Shepherd, 1979).

Depth* km	Velocity km/sec	Geology
0.00	1.5	Water
0.14	1.65	Quaternary
0.51	2.03	U. Tertiary
0.92	2.48	L. Tertiary
1.80	5.08	Mesozoic
5.14	6.22	Paleozoic

(*) depth referred to the upper interface

The traditional pick-and-plot, unreduced travel time method of interpretation was applied to derive crustal models. Fig. 3B is Hussong et al. (1976) generalized composite structural section of Peru trench region and deep ocean derived from "integrating" all crustal models between 8° and 12°S latitude. This section shows oceanic crustal underthrusting on the Nazca plate. Whether such structure is seismically active or not is a question to be answered in the future. For the shallowness of the structure and the major role that water may play on crustal deformation, seismic events associated with this structure might be a small magnitude. Considering the remoteness and the low sensitivity of the closest teleseismic stations no reliable data is available to search for an answer. However, it is without question that compressive stress environments do exist in the oceanic plate. As stated later in this paper, it is proposed that structures of this kind are related to the birth of new Benioff zones.

Crustal model of Meeder et al. (1977), and Hussong et al. (1976) are dissimilar. However, it is surprising that in both models, the 8.3-km/sec refractor begins at about the same depth. Because of the importance of the low velocity layer at the bottom of the crust, it would be interesting to apply Meeder's interpretation procedure to Hussong's et al. data and to investigate evidence for such layer. Keller et al. (1978) model for southern Peru ocean-continent transition should be considered as preliminary. The number of velocity inversions is high. The interpretation needs other constraints besides gravity and reversed travel times, like wave form analysis, for example.

North of Hussong et al. profile, Shepherd (1979) reports Wipperman's results for a 12-km sonobuoy profile shot at about 6.90°S latitude and 80.4°W longitude on the wider part of the continental shelf in the "off-shore part of the N-S trending Sechura basin", Fig. 1-number 1. The results are presented in Table 1. The correlation with Hussong's et al. refractor under the shelf, is in general satisfactory.

Gravity

A regional gravity map of Peru and neighboring ocean covering the active ocean-continent transition zone is presented in Fig. 4. The gravitational anomalies are referred to sea level, thus, the anomalies are the normal Free Air in the ocean, and simple Bouguer on the continent (i.e. Free Air and Bouguer plate corrections applied to the observed gravity). Although the oceanic data from the Nazca Plate Project provides much more information of the fine structure, the regional features remain. Figs. 5 and 6, from Shepherd (1979) and Whitsett (1975) respectively, illustrate this point.

The regional gravitational anomalies cover the country at its full length. From west to east, the main anomalies are:

1) Open ocean: average about zero milligals.
2) Peru-Chile trench with extreme values between -200 mgal, in the southwestern tip of the Nazca ridge, and -150 mgal, in the northwest tip of the Nazca ridge. The anomaly amplitude on the landward extension of the Nazca ridge diminishes significantly on the axis of the trench.
3) Near the coastal line, along the coastal cordillera, a narrow positive anomaly develops with values about +50 mgal in southern Peru, and over +90 mgal in northwest Peru.
4) The Andean anomaly is a dominant feature on the continent with extreme value of about -400 mgal approximately along the axis of the Andean mountains. The axis of the anomaly shows about 200-250 km horizontal offset along the Abancay-Pisco deflection, Fig. 1, with a significant effect on the gravitational anomaly on the axis of the trench off-Pisco, where the trench anomaly becomes more positive, Fig. 6.

In northern Peru, the Paita-Huancabamba deflection have no major effect on the trench axis, Fig. 5. The gravity east of the Andes gradually tends towards the zero value anomaly.

Whitsett's map, Fig. 6, shows the isostatic compensation nature of the Nazca ridge. This effect is absent in ridges off Paita-Huancabamba deflection, where

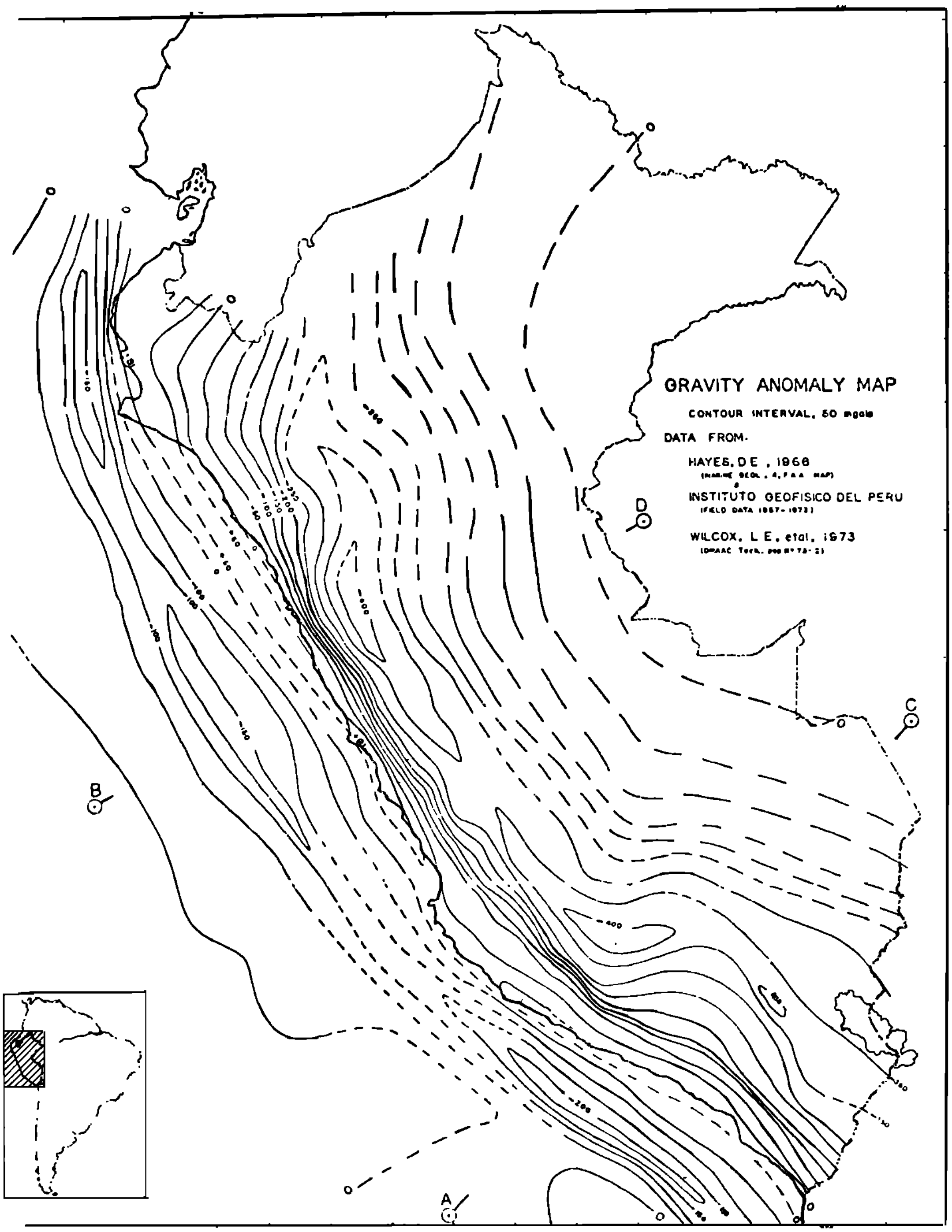


Fig. 4. Gravity anomaly map of Peru. The gravity data was reduced to a sea level datum, with the simple Bouguer plate correction included for the land data, i.e., the anomalies are simple Bouguer on the continent and free air in the ocean.

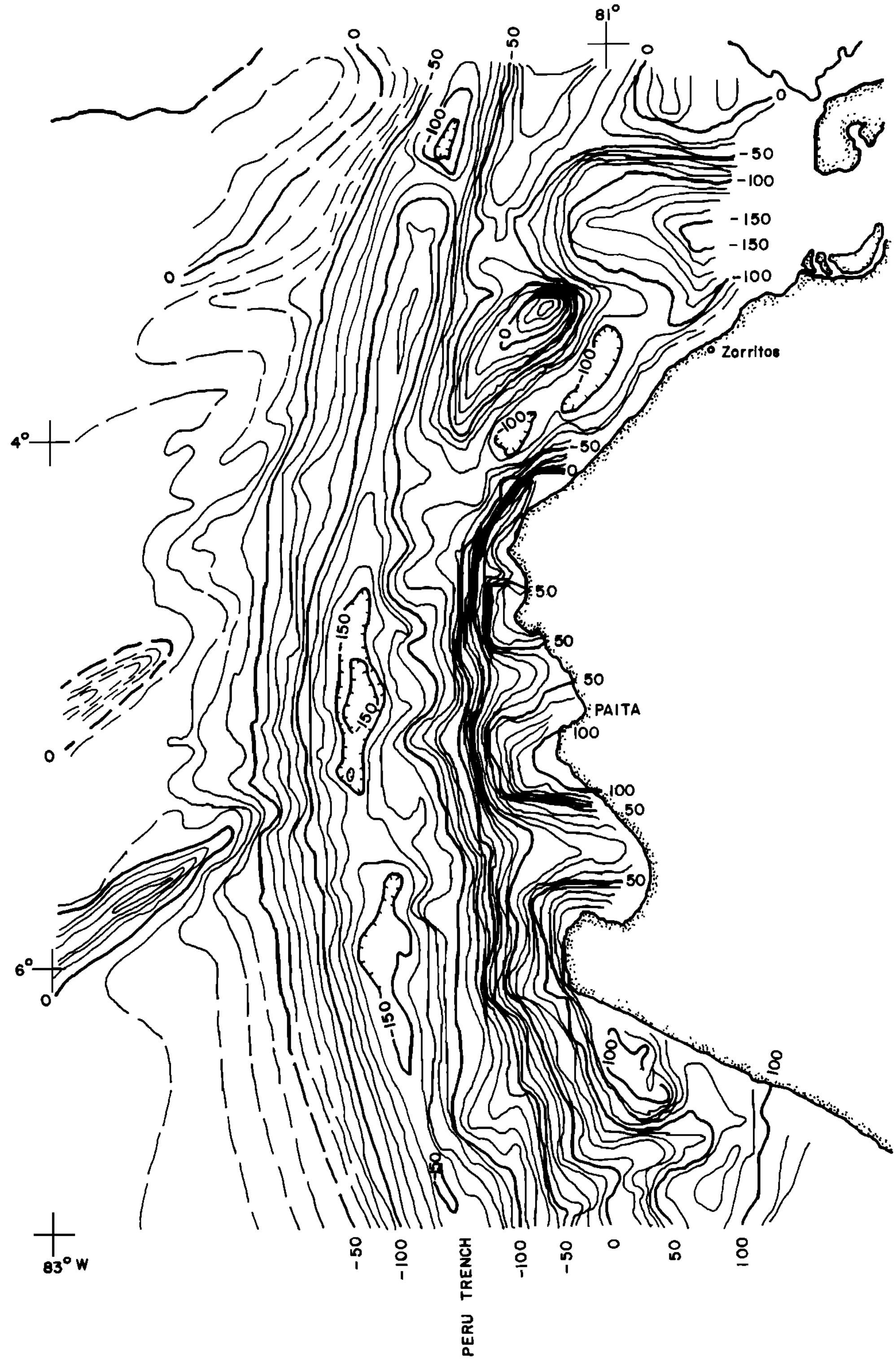


Fig. 5. Detailed gravitational anomaly (free air) map off-shore northwest Peru, 2.5°- 7°S latitudes. The anomalies produced by deep ocean ridges and shelf capes are strong (after Shepherd, 1979).

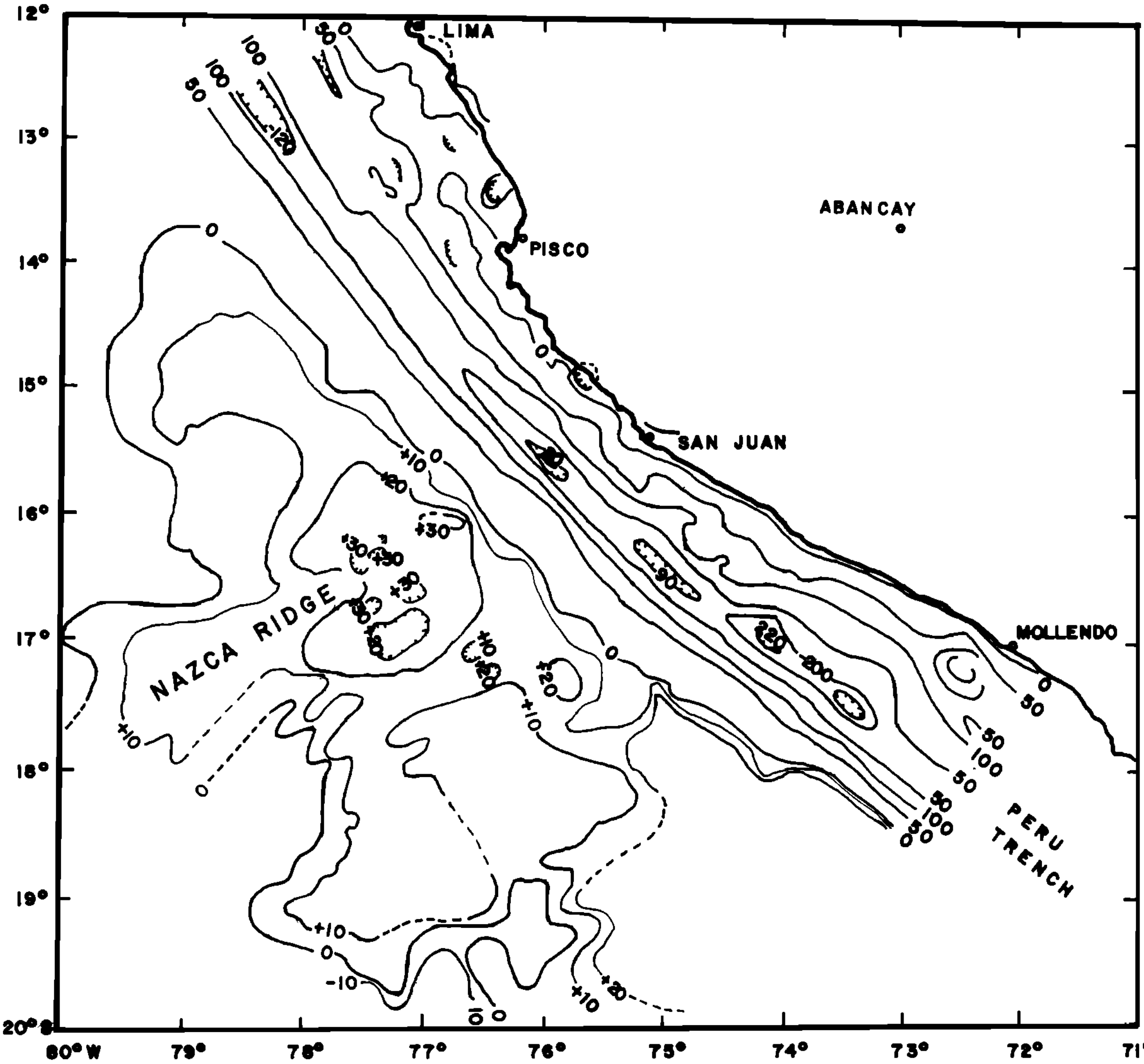


Fig. 6. Detailed gravity anomaly (free air) map off-shore southern Peru. Note the lack of gravimetric expression of the Nazca ridge both under the deep ocean and on the trench axis, i.e., the ridge is isostatically compensated (after Whitsett, 1975).

the gravimetric signature of the topographic elements are striking, Fig. 5.

Electical Conductivity

For more than a decade the Department of Terrestrial Magnetism of Carnegie Institution of Washington, and its South American collaborating institutions gathered data from geomagnetic observations along the Andean mountains and neighboring coastal areas. In 1972, results of the analysis and an interpretation was published as maps showing the co-transfer function between N-S (H) and vertical (Z) components of variations in the geomagnetic field (Aldrich et al., 1972). Their data have been recontoured, and results are presented in Fig. 7. In the same maps, the 3658- and 4023-m bathimetric contours for the Nazca ridge are shown.

According to Aldrich et al. (loc. cit.), the zero contour line marks, Fig. 7A and 7B, the position of the anomalous material closest to surface, assuming a two dimensional structure. The contour pattern of the 64-min period co-transfer function between the horizontal and vertical components of the geomagnetic field, Fig. 7A, is simple. The anomalies tend to be positive towards the Brasilian shield, and negative towards the Peru trench. However, the H-Z co-transfer function at a period of 16 min, Fig. 7B,

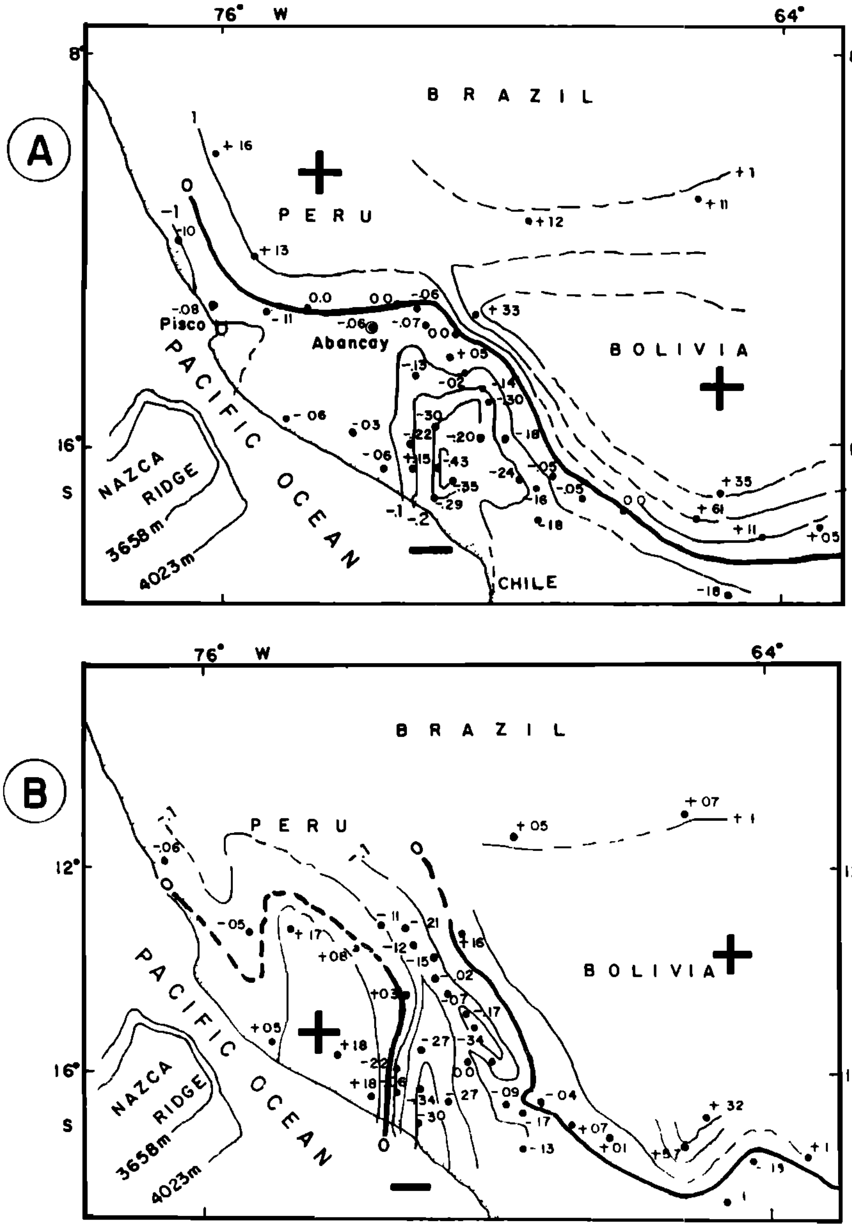


Fig. 7. Co-transfer function between horizontal N-S (H) and vertical (Z) components of variation in the geomagnetic field, data from Aldrich et al. (1972). A. 64-min period, 0.1 units contour interval. B. 16-min period, 0.1 units contour interval. The bathimetric contours of the Nazca ridge are in meters.

has much more structure. There is a well developed positive anomaly in the land extension of the Nazca ridge. This anomaly provides one of first possible evidences for the extension of the Nazca ridge under the continental plate. It would be interesting to map this anomaly in more detail and to complete the study with the appropriate inversion of the data.

As pointed out by Casaverde et al. (1968), the E-W deflection of the zero anomaly contour line (axis of the anomalous body) is coincident with the Abancay-Pisco deflection (Fig. 1). Hence, both gravitational and geomagnetic data correlate well with the tectonic pattern in this region. The Abancay-Pisco deflection is a major relatively deep tectonic feature; possibly associated with the effect of the continuation of the Nazca ridge under the continental plate, and it seems to have played an important role in the definition of the present Benioff-subduction-zone morphology and its evolution on both sides of the deflection axis.

Seismicity and Tectonics

Several models have been proposed to explain the spatial distribution of seismicity north of the Nazca ridge (in the ocean) and the Abancay-Pisco deflection on the continent and the anomalies of the volcanic activity along the Andes.

The arguments for or against any particular model are mainly centred on the interpretation of the seismicity pattern (Barazangi and Isacks, 1976, 1979; Stauder, 1975), and models derived from the interpretation of converted and reflected-refracted seismic phases on what it is believed to be the upper surface of the down going slab, on the Q-structure of the subduction zone (Snoke et al., 1977; Snoke and Sacks, 1975; Okada, 1974).

In 1979 Barazangi and Isacks selected a good quality data set from the International Seismological Center (ISC) catalogue in order to resolve the geometry of the descending Nazca plate beneath the central and north Peru. The plan view of this data is presented, in a modified format, in Figs. 8-I and 8-II. Fig. 8-I shows events with depths between 0 and 70 km, and Fig. 8-II displays events with depths from 70^{+} to 320 km. Barazangi and Isacks (1976) prepared similar plots with a larger set and lesser quality of data. The plan view of such data is reproduced in Figs. 9-I and 9-II in the same format as Figs. 8.

North of the Arica bight, the 0-70 km depth seismic activity, Figs. 8-I and 9-I is distributed in two clear belts: one along the coast and the other along, primarily, the Subandean zone. These belts are the Ica (Nazca)-Paita and the Subandean (Ocola, 1978). The envelopes around the seismic activity of such belts are shown in each figure pair.

The following is evident from figures 8 and 9:

1) The 0-70 km depth seismic belts are not parallel. They seem to converge near the south east edge of the Nazca ridge. Hence, the method presenting seismicity sections by projecting the seismic activity into a vertical plane perpendicular to any of the two belts will give an erroneous picture when block dimensions parallel to trench axis are large.

2) The 0-70 km depth coastal belt follows the general trend of the Peru trench, the Subandean belt does not.

3) The 70^{+}-350 km depth seismic activity shows a definitive segmentation, Figs.8-II and 9-II. There are 4-segments. From south to north these segments are:
i) Taltal (Chile, about 25°S latitude)-Nazca (Peru near 15°S), segment 4. This segment is the best developed and its geometry, taking into account the curvature of the Arica bight, fits the plate subducted under an island arc paradigm. Its general dip is about 30°. In this segment, there are presently active volcanoes in a single active belt approximately parallel to the Peru-Chile trench, Fig. 1. ii) Nazca transition segment: it developes along what might be the continental extension of the Nazca ridge. It marks the transition between segments (2) and (1) from segment (4) (Figs. 8-II and 9-II). This segment includes Barazangi and Isacks tear (Barazangi and Isacks, 1979). However, the morphology of the transition zone seems to be more gradual than expected, as shown by Hasegawa and Sacks (1979). iii) The Subandean segment (2): this segment is nearly parallel to the incipiently developed belt along the coastal area. The activity is not evenly distributed along the segment. Its dip is about 30°, and its axis does not parallel the 0-70 km depth seismic activity belt. iv) Finally, the fourth segment incipiently developed, is the Nazca (Ica)-Paita. The longitudinal axis of this segment, is approximately parallel to the shallow activity segment, and follows the general strike of the Peru trench.

4) There is no significant seismic activity in the block surrounded by belts 1, 2, and 3.

The spatial distribution of the seismic activity and the "uniformity" of the geometrical properties of the Taltal-Nazca segment have been studied in detail by Barazangi and Isacks (1976, 1979). Among the important points made by them were that the thickness of this zone is about 30 km thick, the coherence between the seismicity in the transverse cross-sections was remarkable. There is no major disagreement on this interpretation (see for example besides Barazangi and Isacks' paper; Snoke et al., 1977; Snoke and Sacks, 1975; Rodríguez et al., 1976; Ocola, 1978).

Two Benioff Zone Model

As shown above, the seismic activity north of the Abancay-Pisco deflection and Nazca ridge occurs in multiple belts which are not all parallel. Hence composite

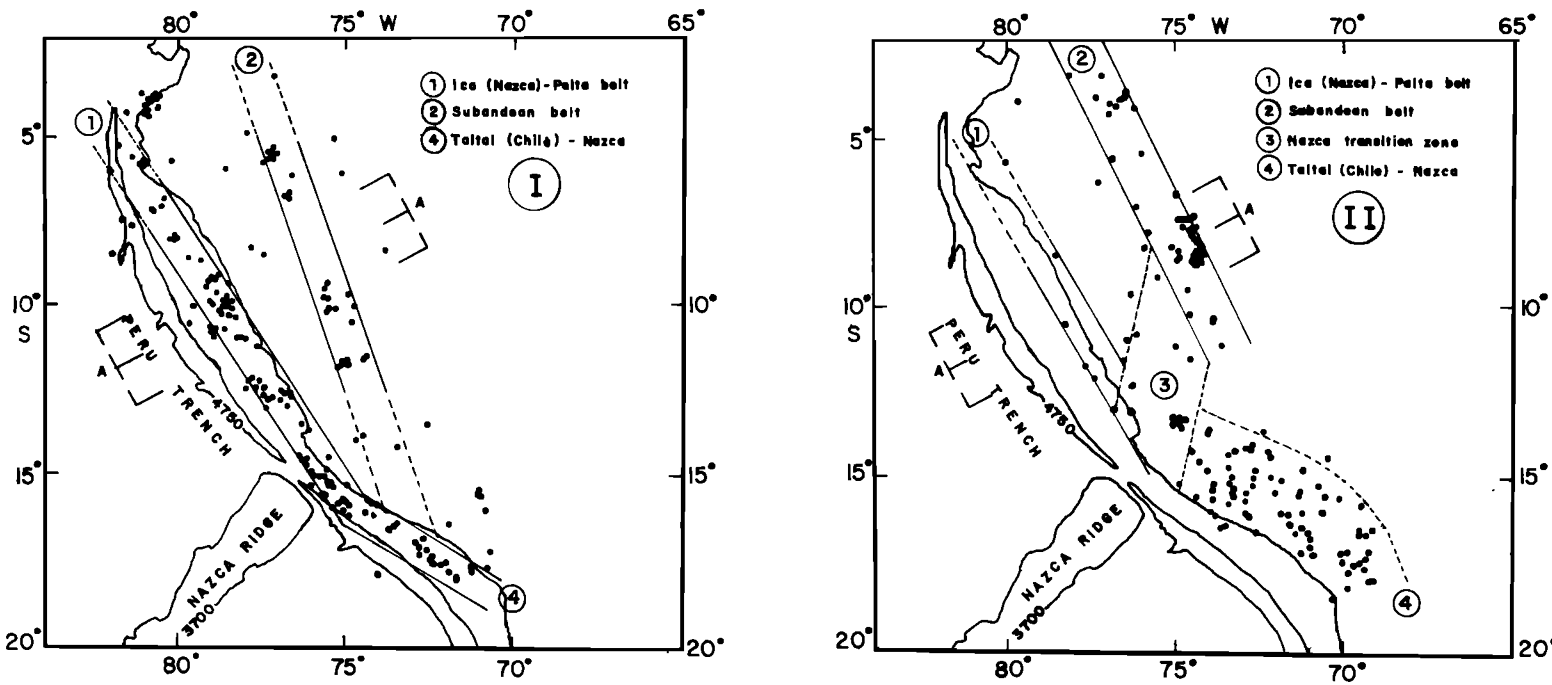


Fig. 8. Seismicity maps of Peru showing the distribution of good-quality data for the period 1964-76 from Barazangi and Isacks (1979, Fig. 3). The envelopes to the seismic activity are the same as Figs. 9-I and II. 8-I: Seismic events with depths between 0 and 70 km. 8-II: Seismic events with depths between 70 and 320 km. Corridor A-A is the same as Barazangi and Isacks' (1979) 1-1 seismic cross section.

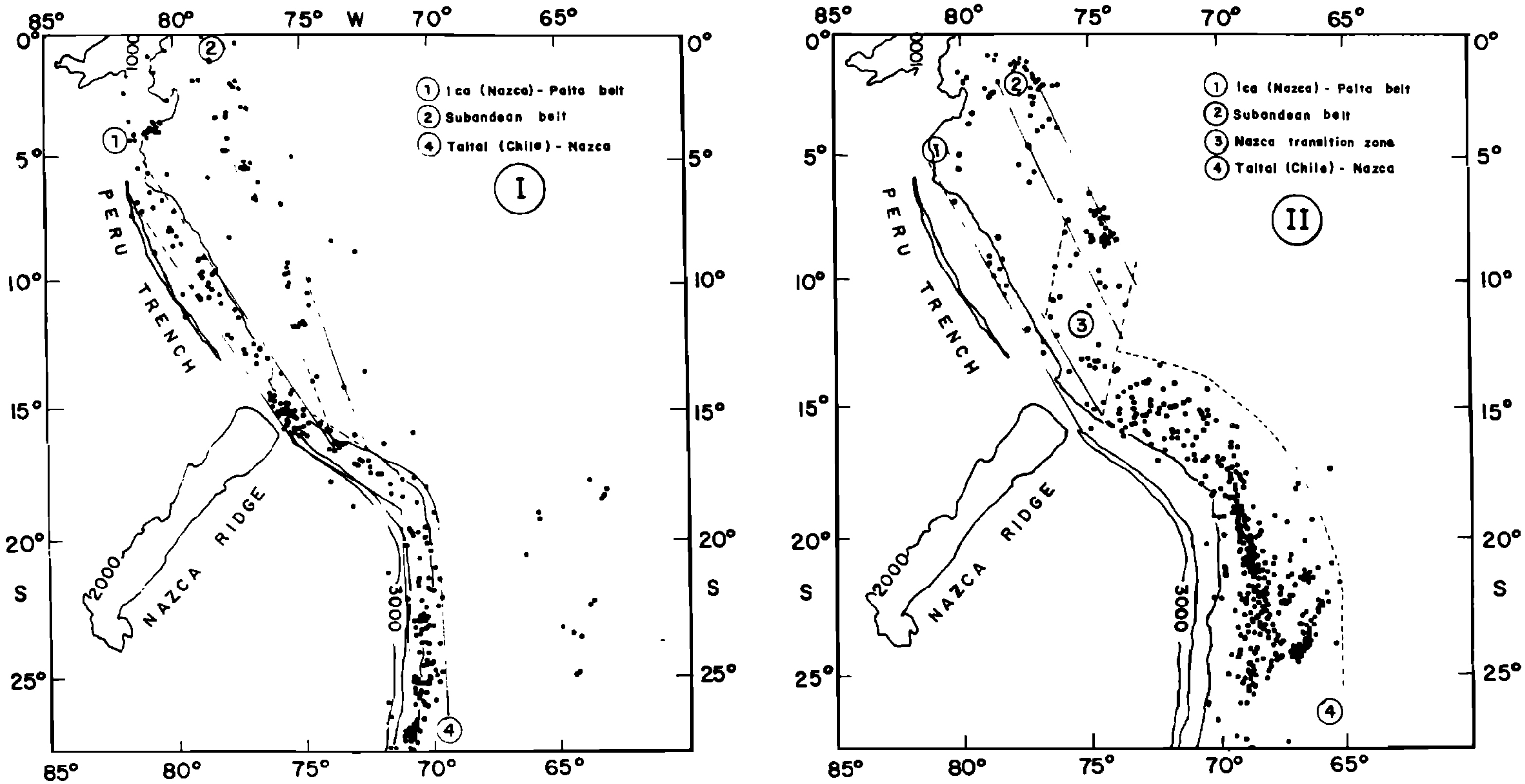


Fig. 9. Seismicity maps between 0° and 27°S latitude data from Barazangi and Isacks (1976, Fig. 1, ISC data). 9-I: Seismic events with depths shallower than 70-km. The seismic belts between the landward projection of the Nazca and Carnegie ridges are not parallel. The three belts: Taltal-Nazca (4), Subandean (2), and Ica (Nazca)-Paita (1) show no obvious segmentation. 9-II: Seismic events with depths between 70 and 320 km. The Subandean seismic activity belt (2) and the Ica-Paita (1) belt tend to be parallel. The Taltal-Nazca belt (4) is very active and well developed. There is a transition belt (3) in the landward extension of the Nazca ridge. The segmentation of the intermediate depth seismic environment is evident.

seismicity cross-sections can not be used to interprete the seismic activity distribution in a vertical plane normal to the general trend of any particular belt or segment, or any tectonic element. The model proposed in this paper, for the seismic activity distribution in the northern segment of Peru is shown in Fig. 10. In this figure, Barazangi and Isacks (1979, Box 1-1, Fig. 3 and Fig. 4: Section 1 class A and B) data is presented together with our preferred interpretation.

In the construction of this model, results from controlled source seismology, and the general dip of 30° have been used for the Benioff slab. The kinematic evolution as well as plausible petrological-geochemical implications are discussed later in this paper. The model considers two Benioff zones. The westernmost zone is associated with the present Peru trench. This zone is young and the seismogenic portions of the subducted slab have not reached a great depth yet. The easternmost Benioff zone is an older one and extends primarily under the eastern flank of the Andes. This zone is believed to be in a process of being extinct. Both Benioff zones are related through a low angle "detachment zone", i.e., the "plate" does not continue from the western Benioff zone to the eastern one. The detachment zone becomes shorter in horizontal extension (along the cross-section), as the Arica bight is approached from the north. The importance of this zone in the kinematic evolution of South American will be discussed later. The Barazangi and Isacks 1976-1979 tear, and Hasegawa and Sacks (1979) near horizontal portion of the "plate" are part of the detachment zone.

Crust- Upper Mantle Dynamics Model

Reconstruction models of past western South American tectonism are primarily based on seismological evidence from natural events, and near surface geological information. The models have not fully considered the South American plate mobility, petrological, and geochemical data of rocks which require magmatic material arising from great depth environments, the episodic nature of the tectonic activity, and other geophysical data. In this section, an attempt is made to integrate multidisciplinary data, and interpreted the South American - Nazca plates kinematics in the Andean subduction zone.

The proposed model assumes that the kinematic evolution of the South American-Nazca plates system is a succession of a locked and unlocked stages. The locked stage is when the mobility of South American plate is minimun or insignificant. The unlocked stage, on the other hand, is that for which the South American plate velocity of displacement is significant or reaches a maximum. The locked phase is characterized by a tectonism primarily deformation (compressional). During this phase the coastal uplift is important the bending of the Benioff slab (i.e., maximum curvature) is near the tectonis trench axis, multiple and well developed Benioff zones coexist. The unlocked phase is characterized by a tectonism associated with significant horizontal displacement of the overrinding South American plate. This displacement takes place along a deep detachment zone involving the upper-mantle and crust. There is no relationship

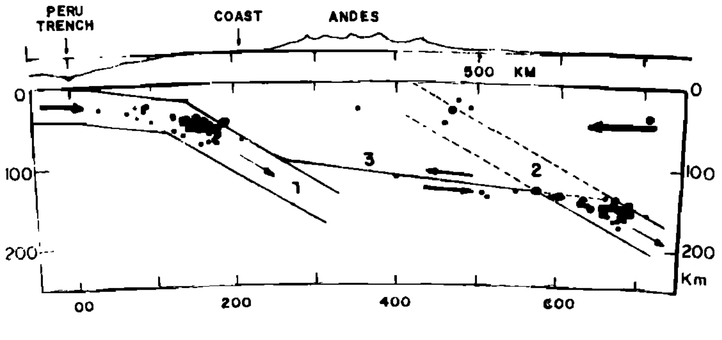


Fig. 10. Seismic cross-section of block A-A, Figs. 9. Data from Barazangi and Isacks (1979, Fig. 4: section1, class A and B): (1) young Benioff zone in process of development, (2) old Benioff zone in process of extinction, (3) detachment zone axis. The arrows indicate direction of displacement.

between the position of the surface contact between the Nazca and South American plates (pseudo trench) and the position of the Benioff zone.

The South American plate displacement speed is controlled primarily by the morphology of the detachment zone, in particular, by its predominant dip (the speed will be greater the smaller the dip), the partial melt zones associated with stress concentrations along the subducted slab, and the rate of subsidance of the oceanic plate (Nazca Plate).

The end of the locked phase is marked by the relatively sudden increase of the overriding South American Plate displacement speed and the birth of a new Benioff zone under the ocean. The end of the unlocked phase, on the other hand, will begin when the South American Plate meets the subducted slab of the new Benioff zone.

Volcanic activity will developed only where the subducted material reaches the appropriate pressure-temperature, and geochemical environments to produce magmatic material.

Kinematics of the Last 14 my

Applying the proposed general model to corridor A-A, Figs. 8-I and 8-II, the last 14 my (my=million years) kinematics of the South American - Nazca plates system is reconstructed. An initial, two intermediate and, one final stage are sketched in Figs. 12 I-IV. It is assumed an average horizontal velocity of displacement 2.2 cm/y for the South American plate, and that the deep section of the subducted slab did not change significantly of position with time. This assumption is justified considering the great thermal and mechanical inertia of the crust and upper mantle directly involved in the subduction process. As a consequence of this assumption, the oceanic surface and South American plate contact (Peru trench) was about 308-km east of the present trench position 14 my ago. At this time, the Benioff zone was fully developed, and partial melt zones might have existed in appropriate magmatic environment along the subducted slab, Fig. 12-I.

According to LePichon (1968), 10 my ago, in late Miocene time, the third cycle of spreading of South Atlantic started. This implies that the South American plate was forced to move westwards at a faster rate producing an increase in stress concentration along the subducted slab, and accelerating the rate of magma formation. After coalescing the small portions of the melt, the magma formed blobs that burnt their way straight up to the upper crust.

The ascent of the blob into the upper mantle and crust can be numerically modeled by a fluid sphere moving vertically upwards in a high viscosity medium. This problem was solved by Lamb (1832), who found that the ascent velocity (U) was given by:

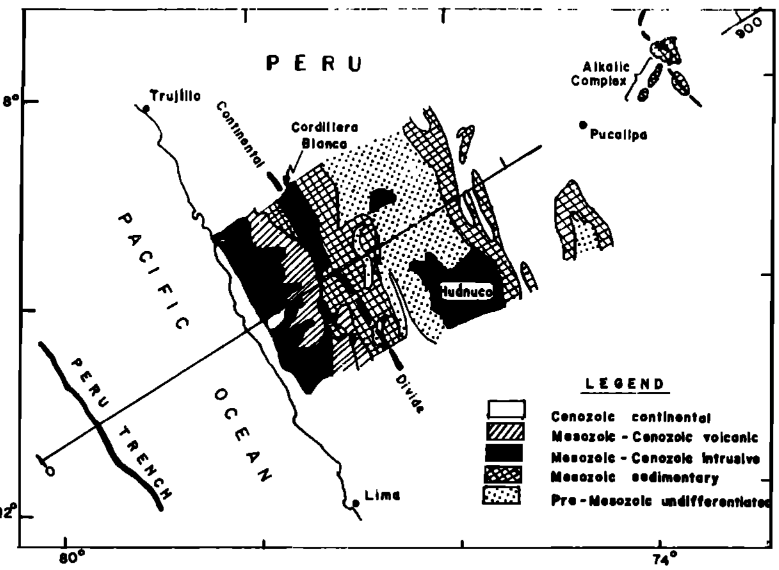


Fig. 11. Regional geologic strip map across the Andes of central Peru (after James, 1979, Fig. 70, modified). This strip coincides approximately with the box A-A of Figs. 8-I and 8-II. The line normal to the trench axis nearly corresponds to seismicity cross-section axis, Fig. 10.

$$U = \frac{1}{3} \; a^2 g \Delta\rho \left| \frac{1+\eta_2/\eta_1}{1+\frac{3}{2}\eta_2/\eta_1} \right| \qquad (1)$$

where η_1 and η_2 are the viscosity of the imbedding medium (upper-mantle and crust), and sphere (magma), respectively; a: the radius of the sphere, g: gravitational acceleration; and $\Delta\rho$ is the density contrast.

Thus for $\eta_1 >> \eta_2$ equation (1) becomes:

$$U = \frac{1}{3} \; \frac{a^2 g \Delta\rho}{\eta_1} \qquad (2)$$

According to James (1977), the magma source for the Pucallpa alkalic complex, Fig. 11 should have, at least, been at 300-km depth. Hence, if it assumed that the magma blobs started their ascent inmediately after the South Mid Atlantic ridge reactivation, then the average ascent velocity of the magma blob can be estimated. For the horizontal distance between present implacement of the Pucallpa alkalic complex and the intersection of the 300-km isobath with the subducted slab is about 150-km, this implies that it had taken about 6.82 my to the South American plate to move over this distance. Thus the blobs ascent velocity is about 4.4 cm/y, which is not unreasonable. Furthermore, if it is assumed that the average blob radius is like a Cordillera Blanca's plutons (Pitcher, 1978), Fig. 11; and a viscosity of 5 x 10^{20} poises for the upper-mantle subsolidus, the 4.4 cm/y ascent velocity implies that the density contrast between the magmatic blob and the mantle-and-crust was 0.86 gm/cc, on the average. It is expected, however, that much larger density contrast might have existed when the blob was still in the mantle. The final implacement of the blobs in the upper crust, though can strongly be guided by pre-existing geologic structures such as regional deep faults or zones of weakness.

When the South Mid Atlantic ridge reactivated, underthrust faults might have developed in the Nazca Plate giving birth to the present Benioff zone, Figs.12 I-III. As the time progressed, the subduction process continued along the old Benioff zone, and the South American Plate migrated westward. At depth, stress concentrated on the slab until the material reached a soft shear state and a detachment zone formed. This detachment zone made the westward displacement of the South American Plate easier.

Sections or portions South American Plate segment between Arica bight and immediately north of the Huancabamba-Paita deflection moved faster or for a longer time, the farther these sections were from the bight. The imprint on the geomorphology of the Andes can be appreciated in Fig. 1. The 3000-m elevation above sea level contour shows this dramatic difference. South of the Abancay-Pisco deflection, the locked stage seems on the great extent and altitude of the Peru-Bolivia altiplano and its complicated tectonics and geology. On the other hand, the segment between the deflections does not show similar feature. It appears that the unlocked stage was dominant.

Comparison With Other Models

There are two independent groups of models for the subduction of the Nazca Plate beneath central Peru: The flat geometry model (Barazangi and Isacks,1976), and the normal dipping one (Snoke et al., 1977). In the first model, the Benioff zone dips about 10°, and it is separated from the shallow activity of the upper 50-km of the overriding South American plate. This model does not explain the normal dip (30° towards the continent) of the seismic activity shallower than 100-km close to the trench nor the significant dip of the activity between 100-and 200-km of depth under the Subandean zone. In the second model, the Benioff zone dips 30°and reaches depths greater than 200-km. This model does not explain the activity under and east of the Andes. Hasegawa and Sacks (1979) proposed a conciliatory model by considering the subducted slab deformed into three segments. The first segment includes the seismicity of the upper 100-km and near the trench; the second segment the flat section of the seismic activity under the Andes and, the third one the activity under east of Andes. The dip of the third segment is about 30° eastward. In this model, it is difficult to explain the mechanism thereby the subducted slab attained the double bending. The model here proposed is simpler. It satisfies the seismicity data as well as the conciliatory model does, but takes into account better the mobility of the South American Plate, the episodic emplacement of linear intrusives along the Andean belt, the systematic variation of the length of the seismicity 'flat segment' between the normal dipping shallow activity near the trench and the intermediate depth seismicity under the Subandean region.

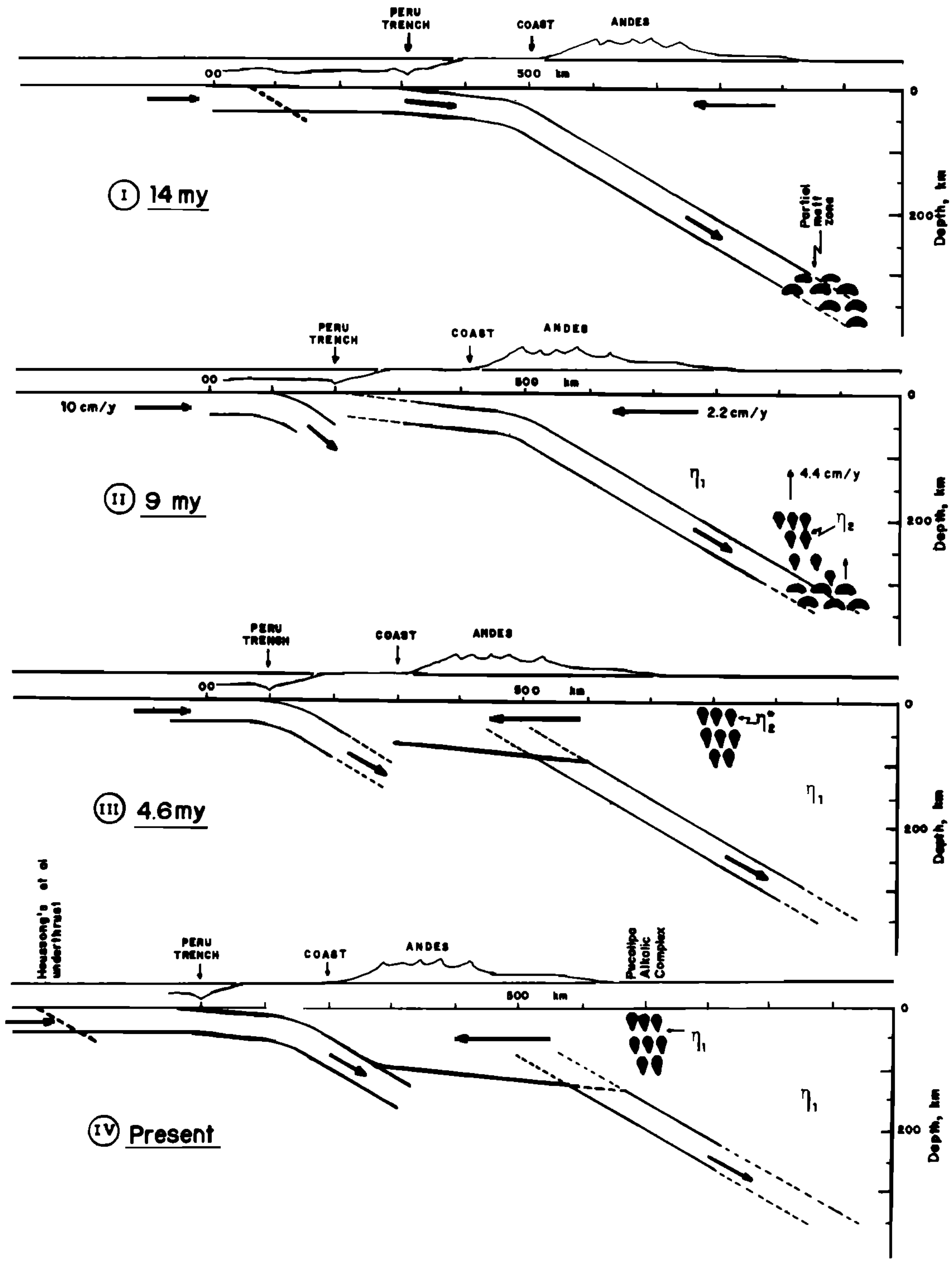


Fig. 12. Kinematic model along corridor A-A, Figs. 8-I and 8-II, diagrams are schematic. I.- Plausible geometry of the Benioff zone 14 my ago. The partial melt zone is one of several possible melting zones along the subducted slab. The heavy solid discontinuous slanted line is potential Hussong's et al. (loc. cit.) underthrust fault. II.- The reactivation of the South Mid Atlantic ridge in its third (late Miocene) cycle at about 10 my increased the partial melt rate of the subducted material, and blobs of low viscosity material were formed. The blobs burnt their

way up into the upper mantle reaching ultimately near surface. For the continental plate was moving westwards the blobs stream path would look like deflected towards the west. This figure cartoons, besides, the old Benioff zone geometry, the westward displacement of the continental plate, the migration of the "trench", and the formation of a new Benioff zone. III.- Schematics of the geometry of main elements at the time when the Pucallpa alkalic complex was implaced near surface, i.e., 4.4-5.4 my ago (Steward, 1971). At this stage, the detachment zone was possibly fully developed, and the old Benioff zone was in process of being extinct. IV.- Present structure of the subduction zone. This figure is the same of Fig. 10 with the Pucallpa alkalic complex and Hussong's et al. (loc, cit.) oceanic underthrust fault added.

Summary and Conclusions

The interest of the earth scientists to solve the Nazca-South American plates dynamic puzzle have been remarkably high. In this paper the most important contributions to the understanding of plate dynamics in collision boundaries have been reviewed. Results from marine geophysical research on the Nazca Plate will be published in a special memoir (L. Kulm, personal communication).

The following are some of the important finding and conclusions for the Peru-North Chile segment of the Nazca-South American plates subduction zone:

i) From controlled source seismology research: A low dipping angle, about 6° of the crust-upper mantle interface, towards the continent off south and central Peru; and underthrust faulting on the oceanic crust in deep ocean.

ii) The gravitational anomalies reduced to a sea level datum reflect the structural complexity and the linear pattern of the major tectonic elements : Peru-trench, Andean tectonic framework, and the major, approximately, E-W tectonic deflections: Abancay-Pisco and Huancabamba-Paita.

iii) The 64-min geomagnetic co-transfer function correlates well with the geologic and tectonic pattern in southern Peru, in particular, with the Abancay-Pisco deflection. In the 16-min period data, however, the correlation is less impressive, but it shows a well developed anomaly on the land extension of the oceanic Nazca ridge. It is proposed that this anomaly is associated with ridge extension under the continent.

iv) A model is proposed to explain the present seismic activity distribution, petrological and geochemical data, the difference in morphology and tectonic pattern between central and southern Peru. The model consists of two normal dipping and different age Benioff zones connected by a detachment zone. This zone affects the upper-mantle and crust. The kinematics history of the Andean subduction zone is also modeled as the result of an alternate succession of the South American plate motion excited by the reactivation of the South Mid Atlantic ridge spreading center. The model does not require that the subducted slab be continuous through the subduction zone nor need to change its dip with depth. The basic differences between the Hasegawa and Sacks (1979) model and the proposed model is the absence of the subducted slab between the western shallow seismicity activity belt and the most eastern intermediate depth belt. Future efforts should be devoted to obtain data with the objective of resolving these differences.

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