Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America

Muawia Barazangi,* Bryan L. Isacks
Department of Geological Sciences, Cornell University
Ithaca, New York 14853

ABSTRACT

A detailed study of the spatial distribution of precisely located hypocenters of South American earthquakes that occurred between lat 0° and 45°S shows that the data can be explained by the simple model of a descending oceanic plate beneath a continental plate and that the following conditions obtain: (1) The hypocenters clearly define five segments of inclined seismic zones, in each of which the zones have relatively uniform dips. The segments beneath northern and central Peru (about lat 2° to 15° S) and beneath central Chile (about lat 27° to 33° S) have very small dips (about 10°), whereas the three segments beneath southern Ecuador (about lat 0° to 2°S), beneath southern Peru and northern Chile (about lat 15° to 27°S), and beneath southern Chile (about lat 33° to 45°S) have steeper dips (25° to 30°). No clear evidence exists for further segmentation of the descending Nazca plate beneath South America. If the two flat segments are in contact with the lower boundary of the continental plate, the thickness of that plate is less than approximately 130 km. This is in marked contrast to the reports of thicknesses exceeding 300 km for the South American continental plate. (2) There is considerable seismic activity within the upper 50 km of the overriding South American plate. This seismic activity is well separated from the inclined seismic zones and probably occurs in the crustal part of the South American plate. Thus, hypocenters in South America are not evenly distributed through about a 300-km-thick zone as previously described. (3) A remarkable correlation exists between the two flat segments of the subducted Nazca plate and the absence of Quaternary volcanism on the South American plate. (4) The transition from the flat Peru segment to the steeper Chile segment is abrupt and is interpreted as a tear in the descending Nazca plate. The tear is located approximately beneath the northern limit of the Altiplano (a high plateau in the Andes), and about 200 km south of the projection of the oceanic Nazca ridge down the subduction zone. (5) A gap in seismic activity exists between depths of 320 and 525 km.

*Present address: Department of Geology, University of Petroleum and Minerals, Dhahran, Saudi Arabia.

INTRODUCTION

South America is a part of one of the major lithospheric plates. Study of the subduction zone along the western margin of this plate provides the opportunity to examine whether the simple model of the descending of oceanic plates beneath an oceanic or small continental block (as developed primarily for the northern and the western Pacific) is also a working model for the subduction of an oceanic plate beneath a continental plate. In this study we show that the simple model of subduction is essentially a valid one for the subduction process beneath South America. However, some features of the interactions and geometries of the descending Nazca plate and the overriding South American plate are quite different from those observed in the northern and western Pacific.

We present here a detailed study of the spatial distribution of South American earthquakes. Previous studies have used, for the most part, the hypocenter file of the United States Geological Survey (USGS) for different time periods (see, for example, Santo, 1969; Isacks and Molnar, 1971; James, 1971; Stauder, 1973, 1975; Sacks and Okada, 1974; Swift and Carr, 1974). Sykes and Hayes (1971) reported results of relocations of South American earthquakes occurring between 1950 and 1964. Some of the studies mentioned above used very much the same data but the authors came to quite different conclusions regarding the tectonics of South America. This is partly a result of contamination of the data set with poor-quality data. In this study we analyzed mainly the data provided by the International Seismological Summary (ISS) and the International Seismological Centre (ISC). We established criteria for selecting good-quality data out of the hypocenter file and rejected all but about 30 percent of the events as a result. This severe rejection procedure is compensated for by considering the entire sample of high-quality data that have accumulated since the late 1950s. We are thus able to resolve features more clearly than is possible with a smaller set of data or one with a large number of poorly located events.

DATA

The earthquakes analyzed in this study are mainly all those located between lat 0° and 45°S and long 60° and 85°W reported by the ISS from 1959 to 1963, by the ISC from 1964 to August 1973, and by the USGS (Earthquake Data Report) from September 1973 to April 1975. However, because few deep earthquakes occur beneath South America, the final data set also includes all the well-located deep events (deeper than 500 km) located by the ISS for the period 1953 to 1958. Data for events located within the Nazca plate or along the Chile Rise are not included.

The ISC data represent the most complete compilation of data on hypocenter locations available on a world-wide basis. These data, however, include a large number of imprecisely located events, mainly because the events of small size, and especially those in areas far from any local seismic stations, are reported by only the very sensitive teleseismic stations. Thus, a selection of the better quality data from the ISS, ISC, and the USGS data file can be made. A selection based on the elimination of events that are located by less than a certain number of stations is often used but will still include poorly located events, even though many of the worst locations are thereby eliminated.

A selection procedure based on the control of depth by local stations, *pP* depth control, and the azimuthal control of the epicenter is used in this study. In this procedure all events reported by the ISS and ISC and the large events of the USGS are examined and either rejected or selected

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depending on (1) the distances and the number of local stations that recorded the events, (2) the consistency and the number of *pP* readings, and finally (3) the azimuthal distribution of the teleseismic stations. The latitude and longitude of the hypocenters as reported by the ISS, ISC, and USGS are used for the selected events; however, we used the depths as obtained from *pP* readings if provided by the ISS, ISC, or USGS.

Of a total of about 5,700 events, only 1,700 events (about 30 percent) were selected for this study. A computer program was used in plotting the selected events on maps and cross sections. The sphericity of the Earth is shown on the sections, and all the sections are plotted without any vertical exaggeration.

GENERAL CHARACTERISTICS OF SEISMICITY

An outstanding and well-known feature of the spatial distribution of hypocenters along South America is the gap in seismic activity between depths of 320 and 525 km (Fig. 1). The deep earthquakes (deeper than 525 km) define two relatively narrow belts of activity, and the number of small-magnitude events relative to the number of large-magnitude events is very low (Suyehiro, 1968; Lomnitz, 1973).

The intermediate-depth activity tends to cluster in space. There is a peak in activity between depths of about 100 and 130 km; most of these events occur between about lat 17° and 24°S near the bend in the coastline between Peru and Chile. This is also the region that has lacked large shallow earthquakes for about the past 100 yr (Kelleher, 1972). The gap in seismic activity at intermediate depths between about lat 25.5°S and 27.0°S is evident; however, this region experienced many large shallow events (Santo, 1969).

SEGMENTATION OF INCLINED SEISMIC ZONE AND APPROXIMATE THICKNESS OF CONTINENTAL SOUTH AMERICAN PLATE

A careful examination of a large-scale map of the seismicity of South America shows that major regional differences exist in the spatial distribution of events with depths greater than about 70 km. It is important to find out how coherent the spatial distribution of events within any region is and whether a single transverse cross section can be made to include all the events within any region and still show a well-defined inclined seismic zone.

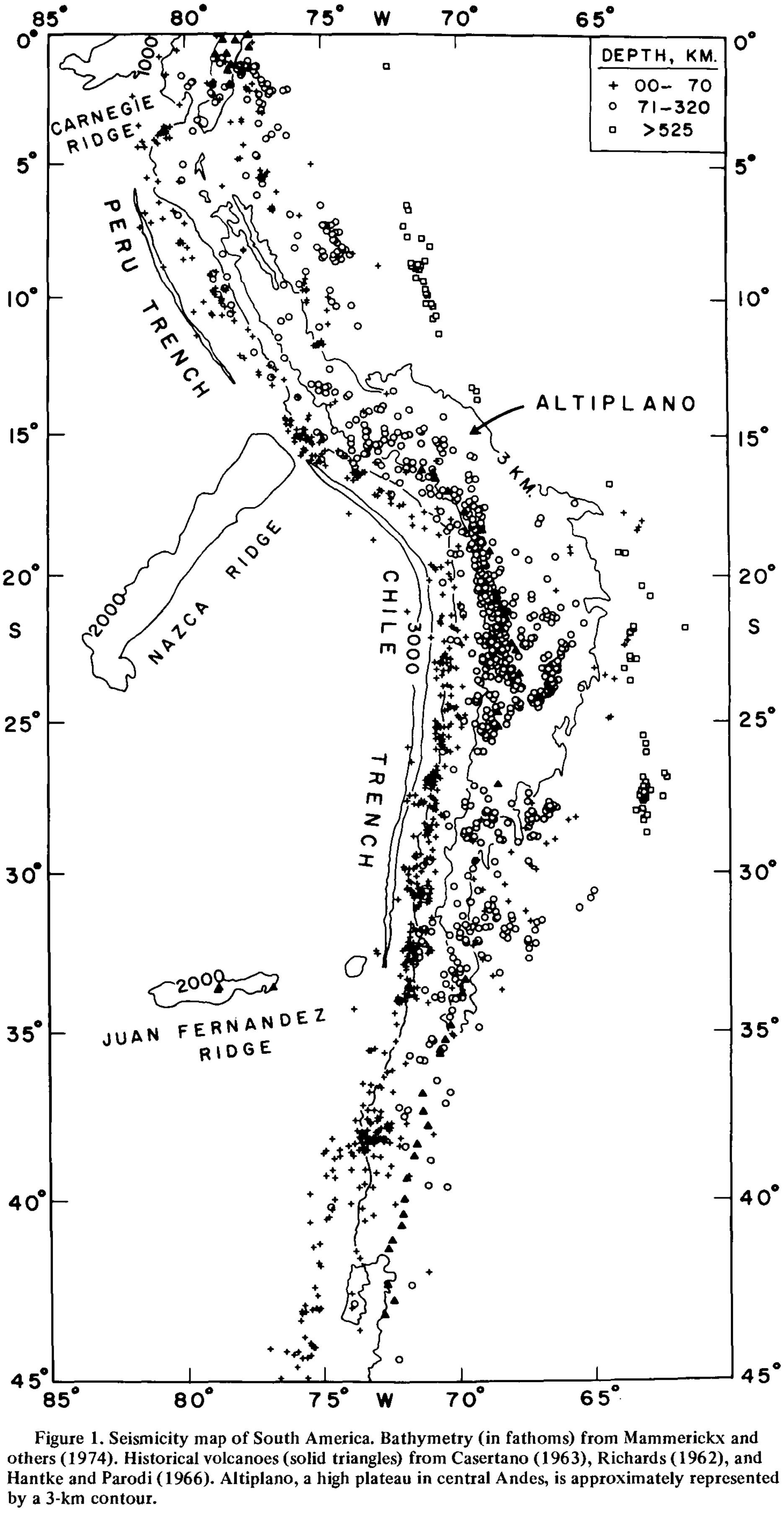

Figure 1. Seismicity map of South America. Bathymetry (in fathoms) from Mammerickx and others (1974). Historical volcanoes (solid triangles) from Casertano (1963), Richards (1962), and Hantke and Parodi (1966). Altiplano, a high plateau in central Andes, is approximately represented by a 3-km contour.

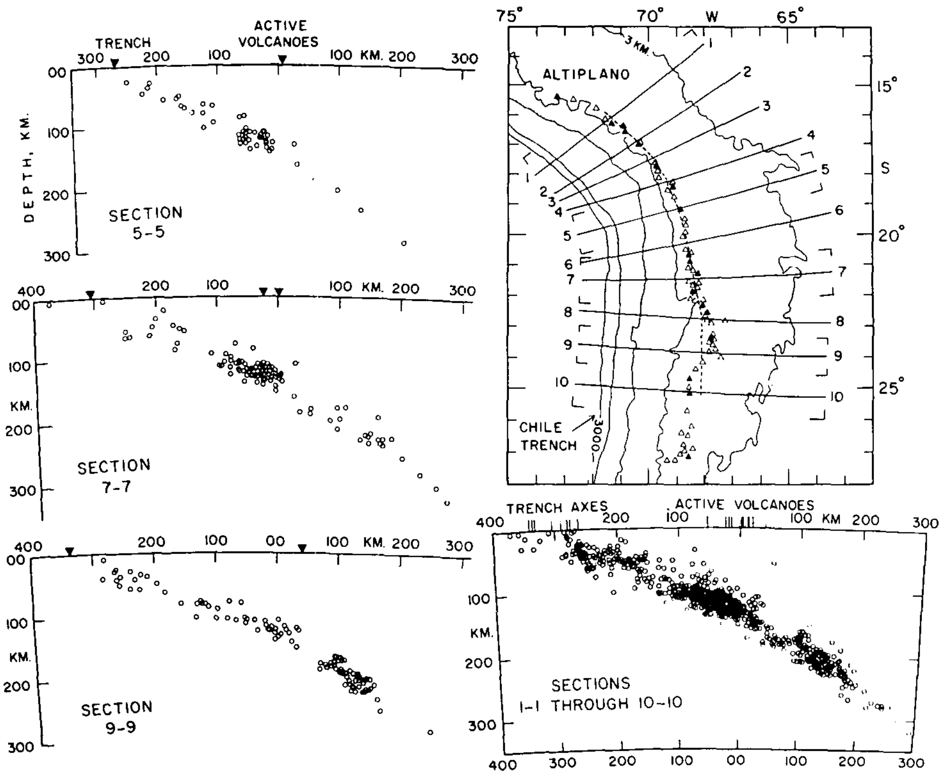

Figure 2. Map of southern Peru–northern Chile region, showing location of 10 cross sections superimposed to obtain composite section shown in lower right-hand corner. Projection of volcanoes and trench axes shown by vertical lines on composite section. Three representative sections are shown on left side. Solid triangles = historical volcanoes; open trianges = Quaternary volcanoes (from Zeil, 1964; Bullard, 1962).

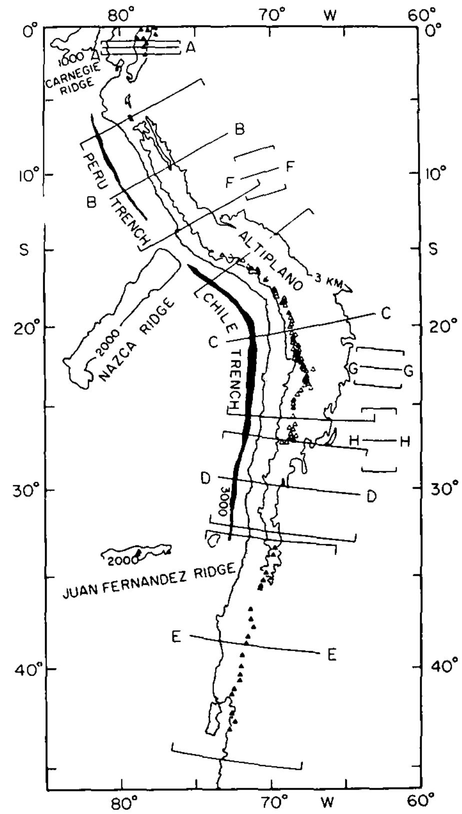

Figure 3. Map showing locations and limits of the cross sections that define five segments of inclined seismic zone (secs. A, B, C, D, E) as well as deep seismic zone (secs. F, G, H) (see Fig. 4). Symbols as in Figures 1 and 2.

The region of southern Peru and northern Chile (about lat 15° to 27°S) has the following characteristics: (1) A major bend in the Chile Trench and in the coastline occurs in this region. (2) The Quaternary volcanoes are well developed (Fig. 2). The volcanoes define a reasonably smooth curve (the volcanic line) in the northern part of the region, with variations that do not exceed about 20 km. However, near lat 22°S the volcanoes start to make a bend that deviates from the volcanic line by about 50 km. (3) The distance between the trench axis and the volcanoes varies from about 250 km in the north to a maximum of about 370 km near lat 24°S. An important question is whether the inclined seismic zone (which is taken to define the descending Nazca plate) beneath this region is reasonably coherent and can be represented by a single transverse cross section or whether abrupt segmentations of the inclined seismic zone are required (as suggested, for example, by Swift and Carr, 1974).

Ten transverse cross sections, each with a total width of about 100 km, were made for the region. The azimuths of the sections are approximately perpendicular to the trench, the volcanic line, and the trend of seismicity (Fig. 2). An important point is that the inclined seismic zone seems to have a thickness of about 30 km. This is not a result of the projection procedure; the "seismic thickness" is very clear on the large-scale map of hypocenters. This apparent thickness probably reflects fault zones within the descending plate (Isacks and Barazangi, 1977). The 10 sections can be superimposed in a way that produces the least amount of scatter in the hypocenters, but at the same time does not have large scatter in the relative positions of the projected volcanoes and the trench axes (Fig. 2). If we choose the center position of the projected volcanoes to represent the zero position for the composite section, then it is clear that the location of this zero position on the map (dashed line in Fig. 2) very much coincides with the volcanoes except near the bend of the volcanoes between about lat 22° and 25°S. However, the seismic sections of events located beneath this bend do match very well with the rest of the sections and do not require any recognizable offset from the other sections.

Thus, the seismicity of the region of southern Peru and northern Chile can be represented by a single transverse composite cross section and still shows a well-defined inclined seismic zone. If we keep in mind the thickness of the seismic zone, then the data do not require any segmentation of the inclined seismic zone (and hence the descending Nazca plate) along the total length of this region. Furthermore, the volcanic line is a better reference for projecting seismic sections than the trench axis, and the variations in the distance between the trench axis and the volcanoes in this region may be a manifestation of accretionary phenomena (Karig and Sharman, 1975).

In the other regions, the projection of seismic cross sections is more straightforward, mainly because the geologic structure (trench, volcanoes, and coastline) and the seismicity trend are less complicated than those of the region discussed above. Tens of seismic cross sections were made for every region with different widths and azimuths to determine the final composite section for any particular region. The results are shown in Figure 3 and Figure 4, sections A through E. The transition from the type of spatial distribution of events in section A to that of B is reasonably well determined (see Figs. 3, 5); the transition from B to C is also well determined and

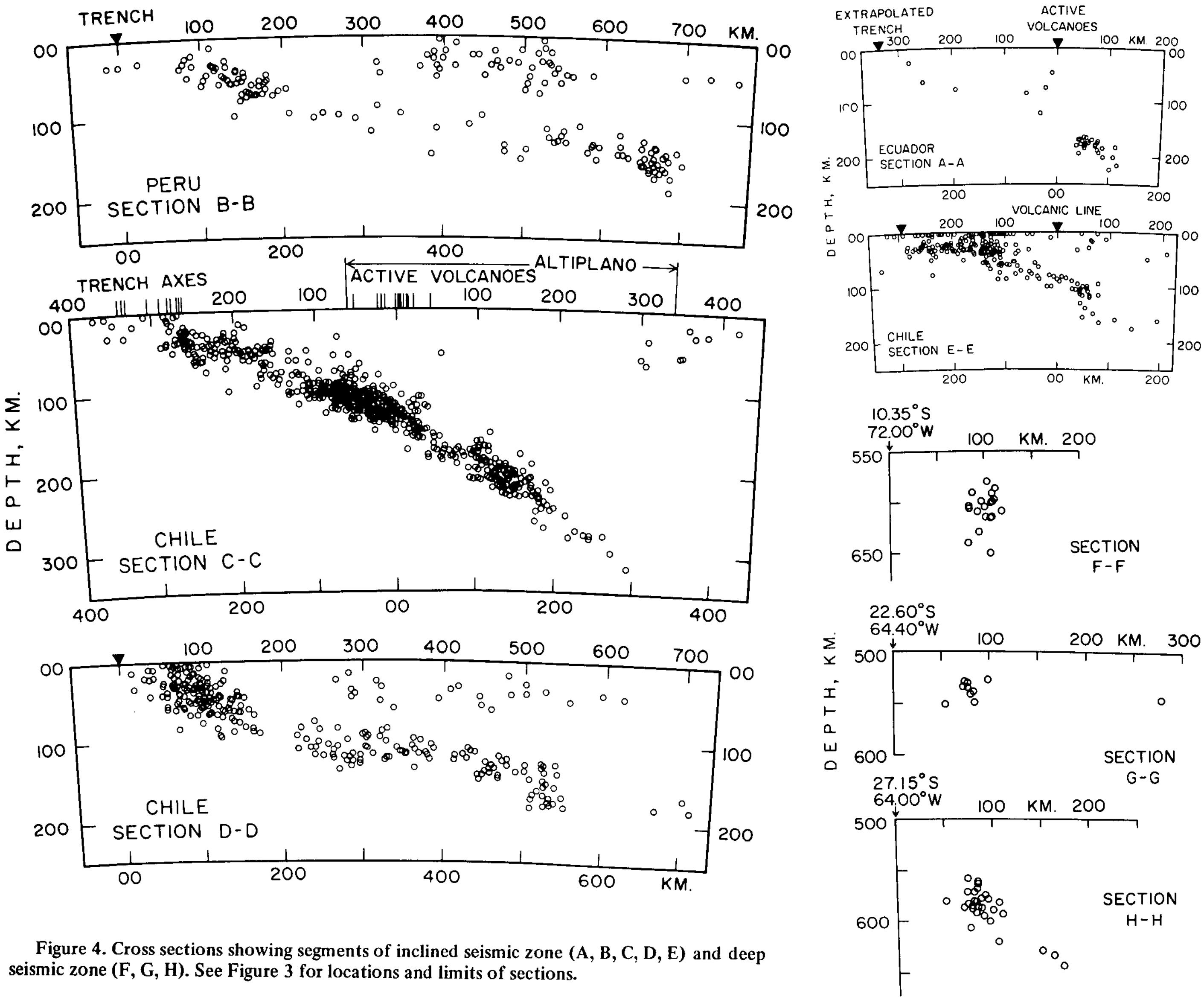

Figure 4. Cross sections showing segments of inclined seismic zone (A, B, C, D, E) and deep seismic zone (F, G, H). See Figure 3 for locations and limits of sections.

will be discussed in detail in a section below; the transition from C to D is poorly determined because of the lack of intermediate-depth events between about lat 25.5° and 27°S; and the transition from D to E is not well determined because of the scarcity of mantle events to the south of about lat 33°S.

Figure 4 shows that cross sections B and D are very similar. For both sections the dip of the inclined seismic zones is about 10°, and for both sections an upward bending of the zones (and hence the descending Nazca plate) near 80 km of depth is suggested by the data; both of these features are unique to South America (see Isacks and Barazangi, 1977). For section B, note that although the number of events at depths of about 100 km and at distances of about 200 to 500 km from the Peru Trench are relatively few, the available data strongly suggest the continuity of the inclined seismic zone.

Figure 4 also shows that section C has an inclined seismic zone with a dip of about 25° to 30°, and that sections A and E appear to be similar to section C. Quaternary volcanoes are located in the South American plate above these three sections (A, C, and E). However, the depth to the seismic zones beneath the volcanoes is noticeably different from section C to section E: about 130 km for C and about 90 km for E.

In summary, five segments of inclined seismic zones are defined beneath the western margin of the South American plate. The available seismic data show no evidence for any further segmentation. It is also important to note that any mixing of data between sections B and C or sections C and D will produce a much thicker seismic zone and will give the false impression that seismic activity occurs in the wedge above the inclined seismic zone.

The two flat segments of the subducted Nazca plate provide a unique opportunity to measure an approximate thickness of the continental South American plate along its western margin. If the flat segments are in contact with the lower boundary of the continental plate and since the intermediate-depth events associated with the two flat segments occur within the descending Nazca plate (Isacks and Molnar, 1971), then it is possible from geometrical considerations to obtain an estimate of the thickness of the overriding South American plate in these two regions of less than about 130 km (see Fig. 8). This result is in marked contrast to recent reports (for example, Jordan, 1975) of thicknesses exceeding 400 km for continental plates.

The widths and the azimuths of the cross sections of deep earthquake zones (Fig. 4, secs. F, G, H) were chosen to produce the least scatter in the seismic zones. Section F (western Brazil) shows a vertical seismic zone about 80 km long, section H

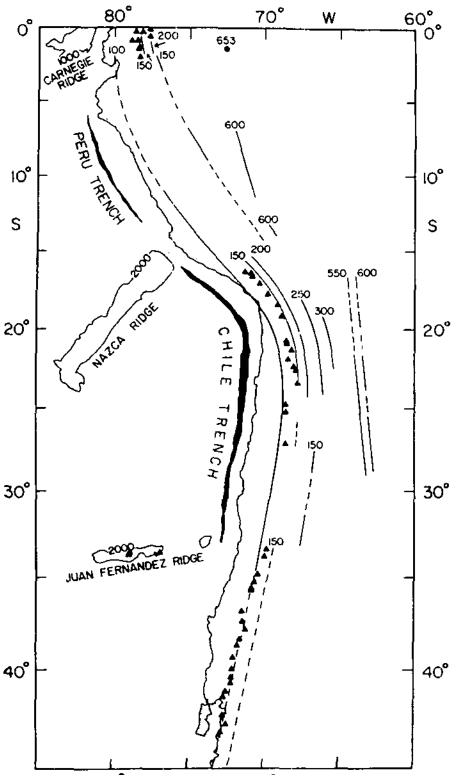

Figure 5. Map showing contours of hypocentral depth to top of inclined seismic zone. Dashed lines indicate that contours are based on fewer data than those shown by solid lines.

(western Argentina) shows a dipping (about 40°) inclined seismic zone about 130 km long, and the events in section G (western Argentina) do not define a clear pattern. Note that the spatial distribution of deep earthquakes overlaps with that of the different segments of the inclined seismic zones at intermediate depths (Figs. 1, 5). Whether the descending Nazca plate is continuous across the gap in seismic activity between 320 and 525 km is not clear. We have suggested (Isacks and Barazangi, 1973) the continuity of the plate for the deep events in western Argentina. However, Snoke and others (1974) showed that our results do not require the continuity of the descending plate.

CORRELATION OF DIP OF DESCENDING NAZCA PLATE WITH VOLCANOES

There is a remarkable correlation between the two flat segments of the inclined seismic zones (secs. B and D, Fig. 4) and the absence of Quaternary volcanoes on the overriding South American plate (Fig. 5). The descending Nazca plate beneath these two regions has a small dip and may follow the contours of the lower boundary of the South American plate. This could leave little or no room for asthenospheric material between the overriding and descending plates. This may explain the absence of volcanism as well as the observed absence of high attenuation of seismic waves in the uppermost mantle beneath these two regions (Molnar and Oliver, 1969; Barazangi and others, 1975; Chinn and others, 1976). In effect, the continental South American plate and the oceanic Nazca plate form a double thickness of lithosphere (Sykes, 1972; Barazangi and others, 1975; Stauder, 1975) of about 200 km; such thickness is in approximate agreement with the results of Sacks and Okada (1974).

In the other three regions where the inclined seismic zones have a steeper dip (25° to 30°), Quaternary volcanism is well developed (Figs. 3, 4, 5). A wedge of asthenospheric material appears to separate the descending Nazca plate from the overriding South American plate. The existence of asthenospheric material seems to be a requirement for the development of active volcanism. The Altiplano, a high plateau in the Andes, closely coincides with the southern Peru–northern Chile region, and an asthenospheric material of extremely high attenuation exists above the inclined seismic zone and beneath most of the Altiplano (Barazangi and others, 1975; Chinn and others, 1976). However, for the Ecuador and southern Chile regions, the nature of the asthenospheric wedge is currently under study (Chinn and others, 1976).

MAJOR TEAR IN DESCENDING NAZCA PLATE

Fortunately, enough data are available to study in some detail the nature of the transition between the gently dipping Peru segment and the more steeply dipping zone beneath southern Peru and northern Chile. The seismicity map in Figure 6 shows that at about the same distance from the trench, events with depths of about 200 km in southern Peru are located adjacent to events with depths of only about 100 km (see also Fig. 5). This indicates that the descending Nazca plate, as defined by these mantle events, has an abrupt vertical offset. The two cross sections shown in Figure 6 clearly illustrate the geometry in this region. The transverse cross sections show that the inclined seismic zone of central Peru coincides with that of southern Peru at depths less than about 100 km. At greater depths, the central Peru zone remains flat at a constant depth of about 100 km, whereas the southern Peru zone has a steeper dip and reaches depths of about 240 km. The longitudinal section also shows the relative sharpness of the transition between the two regions.

The location of the inferred tear in the descending plate is near the northern end of the volcanic line; two Quaternary volcanoes are located about 50 and 100 km northwest of the tear. The inland projection of the aseismic oceanic Nazca ridge beneath the South American plate is located about 200 km northwest of the tear, as are the northern limits of the Altiplano. The exact extent of the northern limits of the high-attenuation zone that exists beneath the Altiplano is not yet determined and is currently under study. There thus may be some genetic relationship between all of the abovce features and the tear. The Nazca ridge may represent a dormant transform fault (Anderson and others, 1976), and hence it is a major zone of weakness in the descending Nazca plate along which the plate may tear. Although the location of the tear is offset from the offshore location of the Nazca ridge, it is tempting to speculate that the ridge had an offset along its trend. Moreover, it is possible that the tear in the descending Nazca plate affects the asthenospheric material adjacent to it and hence contributes to the formation of the high-attenuation zone and the uplifted plateau of the Altiplano.

Another remarkable correlation also seems to exist between the location of the oceanic Juan Fernandez ridge and the transition from the Chilean flat seismic zone (between about lat 27° and 33°S) to the steeper seismic zone in southern Chile (Figs. 1, 5). Active volcanoes are located on the Juan Fernandez ridge. The ridge intersects the Chilean coastline near lat 33°S, where the coastline has a major bend and where the trench becomes increasingly sediment filled. Moreover, the inland projection of the ridge beneath the South American plate closely coincides with the northern limit of the active volcanoes of southern Chile as well as with the end of the Central Valley of Chile (see also Sillitoe, 1974; Vogt and others, 1976). In this case, it is tempting to suggest that the Juan Fernandez ridge forms a zone of weakness in the Nazca plate along which the plate tears as it descends beneath the South American plate.

SHALLOW SEISMIC ACTIVITY WITHIN CONTINENTAL SOUTH AMERICAN PLATE

The shallow seismic zone within the overriding South American plate is probably the most active of all subduction zones on Earth. Figures 1 and 4 show that most of the activity occurs within the upper 50 km of the South American plate, and most of it takes place between depths of about 30 and 50 km. These depths are within the South American crustal thicknesses as reported, for example, by James (1971) and Ocola and Meyer (1972). As Figure 4 shows, the shallow seismic activity is separated from the well-defined inclined seismic zones. Thus, there is no evidence for any seismic activity within the mantle part of the South American plate.

A striking observation is that although the shallow seismic activity is relatively dispersed, most of the activity is near the eastern flanks (sub-Andean zone) of the Andes regardless of the distance of the sub-Andean zone from the trench (Figs. 1, 4). Moreover, it appears that most of the large events are located above the two shallow-dipping seismic zones (secs. B and D, Fig. 4). This could be the result of the strong interaction between the South American plate and the descending Nazca plate in these two regions. The observed high compressive stresses in the Peru region (Stauder, 1975) could contribute to the lack of volcanism in the region (Sykes, 1972).

LINEAR FEATURES IN SPATIAL DISTRIBUTION OF CHILEAN INTERMEDIATE EARTHQUAKES

The distribution of intermediate earthquakes in South America tends to cluster in space. A strikingly linear distribution of events occurs between about lat 17° and 23°S and has a trend of about N18°W, and most of the events are between 110 and 130 km deep (Fig. 7). In fact, at a closer look, this linear feature seems to be formed of two approximately parallel linear features. Figure 7 also shows the compression, tension, and null axes of seven focal mechanisms obtained by Isacks and Molnar (1971) and Stauder (1973) for events located along the linear feature. Isacks and Molnar and Stauder interpreted these mechanisms to indicate extensional stresses parallel to the inclined seismic zone. In each case, one of the nodal planes of these mechanisms closely coincides with the trend of the linear feature, and hence these planes could possibly represent fault planes (Fig. 7). Failure accompanied by these large intermediate events could occur along a zone of weakness associated with the linear feature within the subducted Nazca plate. Moreover, the linearity and continuity of the spatial distribution of events within the linear feature is evidence that there is no segmentation of the inclined seismic zone in this region.

Two other clusters of activity are shown in Figure 7. Both have an approximate strike of northeast-southwest, and both represent linear pencil-shaped zones that dip obliquely to the overall dip of the inclined seismic zone. The first cluster begins near lat 24.5°S, long 67°W with events of about 170-km depth and ends toward the northeast with events of about 220-km depth. Note that this linear activity is approximately parallel to the contorted part of the volcanic line in central Chile (Figs. 2, 7). The second cluster begins near the end of the first one at about 200-km depth and ends at about 270-km depth. Again, these two dipping "lines" of activity may represent relatively narrow zones of weakness within the descending Nazca plate.

SUMMARY

The data presented show that the oceanic Nazca plate is divided into five distinct segments as it descends beneath the continental South American plate. Two of the segments (one beneath central and northern Peru and the other beneath central Chile between lat 27° and 33°S) are relatively flat and may follow the contours of the lower boundary of the South American plate, with little or no asthenospheric material in between them. The regions above these two segments are characterized by the lack of Quaternary volcanism (Fig. 8). The other three segments (beneath Ecuador, beneath southern

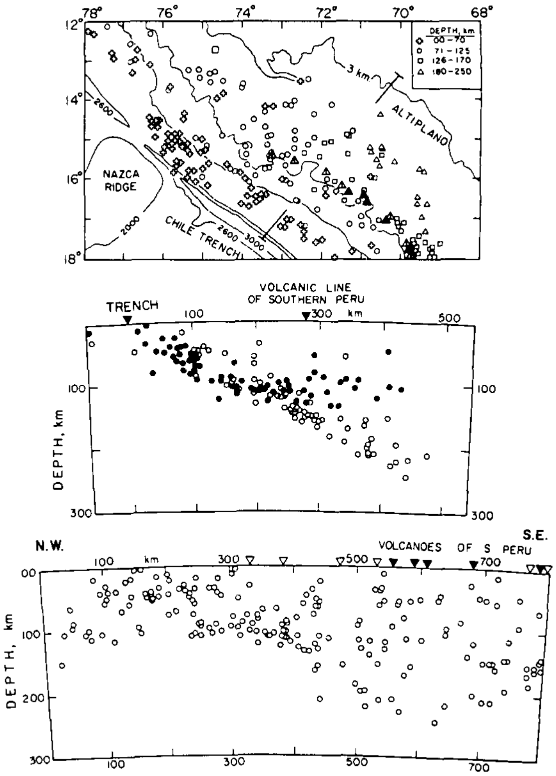

Figure 6. Map view, cross section, and longitudinal section of distribution of earthquakes in southern Peru and northern Chile, showing abrupt increase in hypocenter depth in passing from flat Peru segment to more steeply dipping northern Chile segment. Filled and open circles in middle cross section are for events to northwest and southeast, respectively, of line indicated in map view. Longitudinal section is perpendicular to that line. Solid triangles = historical volcanoes; large open triangles (and divided triangles in map view) = Quaternary volcanoes.

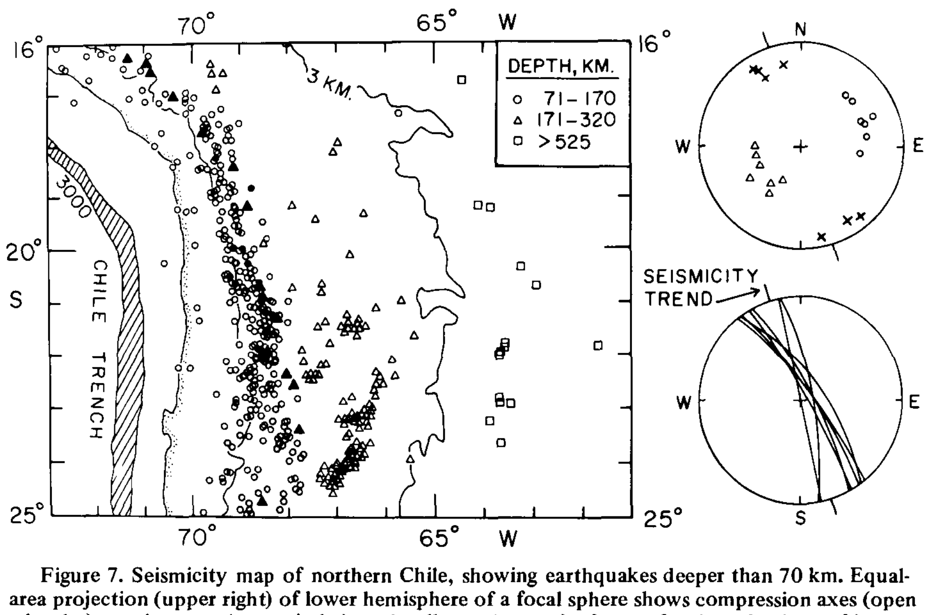

Figure 7. Seismicity map of northern Chile, showing earthquakes deeper than 70 km. Equal-area projection (upper right) of lower hemisphere of a focal sphere shows compression axes (open triangles), tension axes (open circles), and null axes (crosses) of seven focal mechanisms of intermediate-depth events (filled circles on map). Focal plot (lower right) shows one of the nodal planes for each of the seven focal mechanisms.

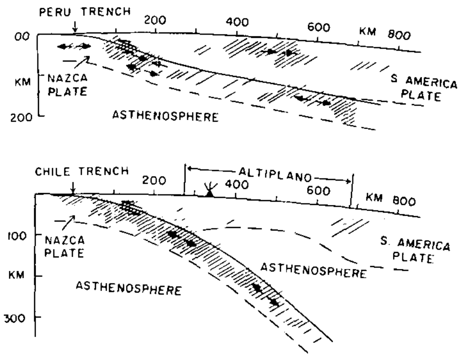

Figure 8. Two cross sections showing inferred geometries of descending Nazca plate and continental South American plate in central Peru and in northern Chile. Inclined thin lines schematically represent distribution of hypocenters. Results obtained from focal-mechanism data by Isacks and Molnar (1971), Stauder (1973, 1975), and Isacks and Barazangi (1977) indicate thrusting of Nazca plate beneath South America (thin arrows), downdip compression or tension within descending Nazca plate, horizontal tension beneath trench, and horizontal compression within South American plate (heavy arrows). Thickness of South American plate to east of Altiplano in Chile is taken to be same as that found in Peru.

Peru–northern Chile, and beneath southern Chile) are steeper (25° to 30°) than the two flat segments, and asthenospheric material appears to separate them from the overriding South American plate. The regions above these three segments have abundant active volcanism. The transition from the flat Peru segment to the steeper segment to the south occurs along a major tear in the descending Nazca plate. A thickness of less than about 130 km is estimated for the continental South American plate along its western margin.

Recently, Jischke (1975) proposed a model for the dynamics of the descending plates that may be applicable, in particular, to the South American arc. He argued that if the region between the descending and overriding plates is narrow and varies with depth, hydrodynamic forces arise that can balance the gravitational forces acting on the descending plate, and hence the plate will have a tendency to adhere to the lower boundary of the overriding plate. The geometry of the two flat segments of the descending Nazca plate in Peru and Chile can be explained by Jischke's model.

Although there has been no volcanism in central and northern Peru during Quaternary time, the region had considerable volcanism during Miocene and Pliocene time (Giletti and Day, 1968; Noble and others, 1974). If the lack of active volcanism is directly related to the flat geometry of the descending Nazca plate beneath the region, then we infer that the present-day geometry is not a steady-state process and that the descending plate must have had a steeper dip during Pliocene time (that is, similar probably to the present situation in northern Chile). One can speculate that in the future the gravitational forces acting on the flat segment of Peru will overcome the hydrodynamic forces that are holding the plate flat, leading to the separation of the descending Nazca plate from the South American plate and the flow of asthenospheric material into the wedge between the two plates. This would result in an episode of volcanism. It is possible that the present geometry of plates in northern Chile is a result of such a mechanism.

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