GEOPHYSICAL RESEARCH LETTERS, VOL. 11, NO. 1, PAGES 38-41, JANUARY 1984

THE CONFIGURATION OF THE SEISMIC ZONE AND THE DOWNGOING SLAB IN SOUTHERN PERU

F. Grange[1], P. Cunningham[2], J. Gagnepain[3], D. Hatzfeld[1], P. Molnar[2],
L. Ocola[4], A. Rodrígues[5], S.W. Roecker[2], J.M. Stock[2,6], G. Suárez[2,7,8]

Abstract. Using data from temporary networks of portable seismographs in southern Peru, we located 888 shallow and intermediate depth events near a proposed discontinuity in the seismic zone there. These events reveal a prominent contortion, instead of a discontinuity, that trends approximately N80°E, parallel to the direction of relative plate motion. North of about 15°S, the seismic zone beneath Peru is nearly horizontal, but south of about 15.5°S, it dips at about 25°. Volcanoes lie above the more steeply dipping zone where earthquakes occur between 120 and 140 km, and the volcanic line in southern Peru stops abruptly at the contortion.

Introduction

One of the fundamental aspects of plate tectonics is that zones of intermediate and deep focus earthquakes usually define subducted slabs of oceanic lithosphere (Isacks, Oliver and Sykes, 1968). Although exceptions exist (Chen and Molnar, 1983; Hatzfeld and Frogneux, 1981; Roecker, 1982), the vast majority of well located intermediate and deep focus earthquakes are part of well defined, inclined, and essentially planar seismic zones where active subduction of oceanic lithosphere is known to be occurring. Because intermediate and deep focus earthquakes occur within the downgoing slab, the shape of the seismic zone can be used to map the configuration of the downgoing slab. Therefore, variations in the geometry of the seismic zone represent discontinuities or contortions of the downgoing slab. These features are well-established by accurate locations of earthquakes recorded at teleseismic distances (e.g. Carr et al., 1973; Isacks and Molnar, 1971; Sykes, 1966), but little work has been done to refine the shape of any contortion with dense local networks and a large number of well located events. Here we report the results of such a study of the contortion of the seismic zone in southern Peru.

Barazangi and Isacks (1976; 1978) showed that the dip of the seismic zone beneath South America changes abruptly in several places so as to divide the slab into segments that dip either at a gentle angle of less than 15° or at a steeper angle of 25-35°. They showed that the zone dips at a gentle angle beneath northern and central Peru but at a steeper angle beneath southern Peru, Bolivia and Northern Chile. By projecting hypocenters on profiles perpendicular to the coast, they inferred a discontinuity in the seismic zone, and therefore a tear in the slab, trending approximately northeast through 16°S, 72°W in southern Peru. They also noted that Quaternary volcanism is absent along most of the Peruvian Andes where the seismic zone dips at a gentle angle but that active or recently active volcanoes do lie above the area where the slab dips more steeply. The northernmost active volcano in southern Peru is about 100 km northwest of where they inferred the tear to be.

The change in dip of the seismic zone in southern Peru is inescapable but there are too few intermediate depth earthquakes located with teleseismic data to show a clear discontinuity instead of a contortion in the zone. Using a network operated in collaboration with the Universidad Nacional de San Augustin in Arequipa, Hasegawa and Sacks (1981) located many intermediate depth events in Southern Peru, many more than Barazangi and Isacks had used. Their network is mostly along the coast and not well positioned to study events beneath the high Andes, and the uncertainties in their locations are difficult to estimate. Nevertheless, their calculated locations show that any discontinuity in the seismic zone must be small and that the zone is markedly contorted.

Methods and Quality of Data

Unaware of Hasegawa and Sacks's work we began a field investigation of microearthquake seismicity in southern Peru for four weeks in 1980 using 17 stations and returned in 1981 for six more weeks with 18 stations. One motivation was to examine the intermediate depth seismicity near Barazangi and Isacks's "tear", and here we report the results relevant to that problem. Elsewhere we report fault plane solutions, and we discuss both shallow focus events and numerous tests to determine the quality of locations (Grange, 1983).

Field procedures and methods of data analysis were similar to those reported elsewhere (e.g. Chatelain et al, 1980). We estimate that errors in arrival times of P waves are about 0.1 s, and we used S waves when arrival times with uncertainties of less than about 0.8 s could be

---

[1] Laboratoire de Géophysique Interne, IRIGM, Université Scientifique et Medicale de Grenoble, BP68 38402 Saint Martin d'Heres, France

[2] Department of Earth and Planetary Sciences, Massachusetts Institute of Technology Cambridge, Mass. 02139, USA

[3] Institut de Physique du Globe, Université de Paris VI, 4 Place Jussieu, 75006 Paris, France

[4] Instituto Geofisico del Peru, Apartado 3747, Lima 100, Peru

[5] Instituto Geofisico, Universidad Nacional de San Augustin, Apartado 751, Arequipa, Peru

[6] (present address) U.S. Geol. Survey, Menlo Park, CA 94025, USA

[7] (present address) Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY 10964, USA

[8] Order of junior authors alphabetical

Paper number 3L1785.
0094-8276/84/003L-1785$03.00

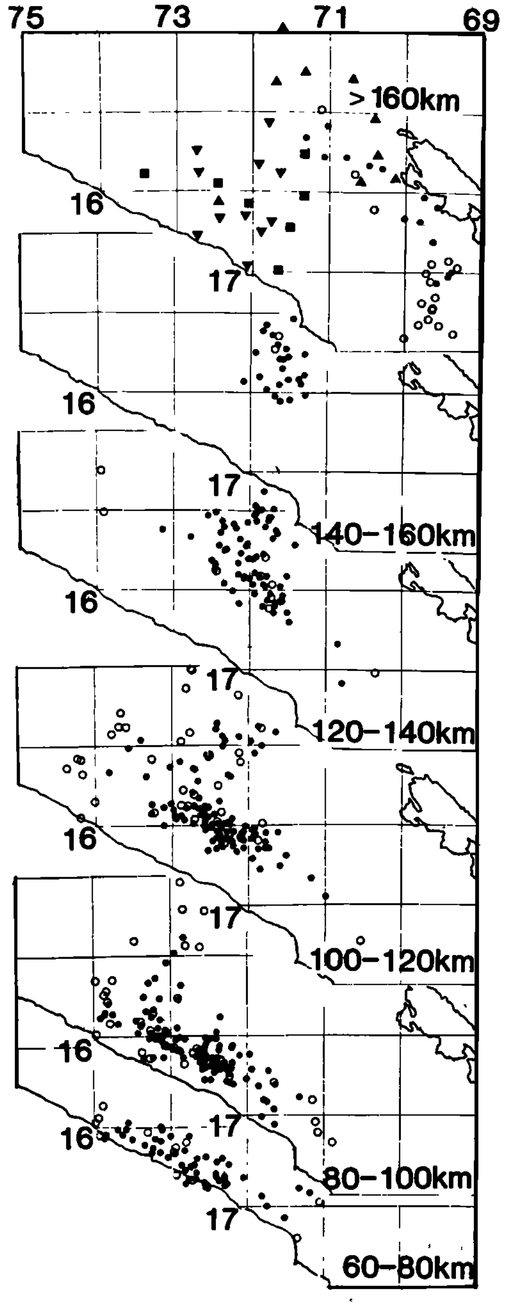

Fig. 1. Maps of epicenters of earthquakes in different depth intervals. In the uppermost map, closed triangles, inverted closed triangles, and closed squares indicate the locations of stations used in the 1980 investigation, stations used in the 1981 investigation, and permanent stations, respectively. Closed circles show epicenters with uncertainties less than 10 km (usually less than 5 km) and with depths of uncertainty by less than 10 km. Open circles show epicenters with uncertainties of less than 15 km in the northwest and 20 km in the southeast. Note broadening of zone in northern part for depths of 110 to 130 km, indicating a flattening of it.

picked. To locate the events we used the program HYPOINVERSE (Klein, 1978). We located events with different velocity structures and different ratios of v_p/v_s to examine the stability of the locations. Among 250 events from 1980 and some 3000 from 1981 we found that locations for 888 were stable; for each event calculated locations with different v_p/v_s were within 10 km of one another. We then made a series of tests both with synthetic data and with subsets of our arrival times to evaluate the quality of the computed locations. Using synthetic data we examined the effects of corrections due to differences in elevations of stations and of a laterally varying structure (e.g. increasing crustal thickness to the east) on the quality of locations and their uncertainties. We also carried out an extensive series of tests with selected events in different areas and recorded by various numbers of stations in 1980 and 1981. We used a simple layered structure, but with different velocities, depths to the Moho, and v_p/v_s ratios. Based on these tests, we developed the following criteria to select reliably located events and to assign errors to them.

1) For the most reliably located events eight or more phases including at least one S-wave arrival time were used.

2) The root mean square values of travel time residuals (RMS) are less than 0.4 s when the number of reported arrival times (N) is larger than 25; RMS < 0.35 s when $15 < N < 25$; and RMS < 0.30 s when $8 < N < 15$.

3) When the maximum azimuthal aperture without stations (GAP) measured from the epicenter is larger than 300°, the epicentral distance to the nearest station (DMIN) is less than one-half the computed focal depth; and when GAP is less than 300°, DMIN is smaller than the computed focal depth for earthquakes deeper than 60 km, and less than twice the computed focal depth for events shallower than 60 km.

For locations meeting these criteria we estimate errors in locations of intermediate depth events to be less than 7 km, with errors in epicentral coordinates less than 5 km. For shallow events, errors seem to be less than 5 km, with epicenters usually uncertain by only 3 km. Among the 888 events with stable locations, 592 met the criteria listed above (dark symbols in figures 1-3). We estimate that the uncertainties in locations of the remaining 296 events (open symbols in figures 1-3) are about two times those in the first group. They were located with at least 6 phases including one S phase.

Results and Implications

The distribution of well located seismicity corroborates Barazangi and Isacks's contention that the dip of the seismic zone is much gentler north of about 16°S than south of it. These data, however, imply that Hasegawa and Sacks (1981) were correct in inferring that the zone is contorted and not discontinuous. At the same time, our data show that the orientation of the contortion is not perpendicular to the coast but instead is essentially parallel to the direction of relative plate motion (~80°E), which is virtually the same as the direction of the Nazca plate with respect to a fixed hot-spot frame of reference (Minster and Jordan, 1978). This is clear from maps of earthquakes in different depth ranges (Figure 1). For depths between 60 and 80 km, epicenters are confined to a narrow zone

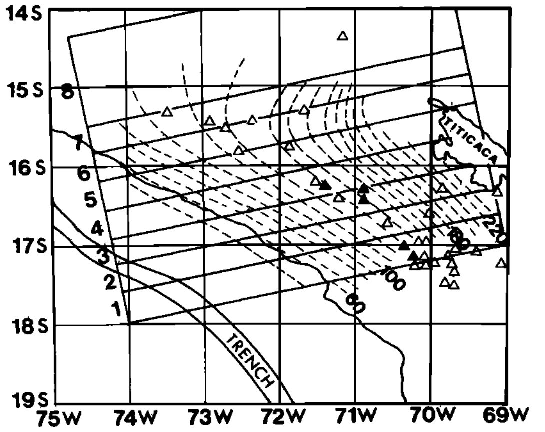

Fig. 2. Contours for events in different depth ranges. Note change in orientations of contours from being parallel to the coast to more northerly trends near 15° to 15.5°S. Triangles show locations of recently active (open) and extinct (closed) volcanoes (from Dalmayrac et al, 1980). The series of rectangles shows the regions from which the cross-sections in Figure 3 are taken. These rectangles are oriented in the direction of relative plate motion (Minster and Jordan, 1978).

along the coast. Between 80 and 100 km, epicenters spread over a broad area north of 16°S but define a narrow belt to the south. The broad area implies a gentle dip of the seismic zone. Between 100 and 120 km and 120 and 140 km, the same pattern exists, but the broad areas of epicenters grow eastward with depth. Contouring the depths of the seismic zone (Figure 2) shows a steady increase northeastward beneath southern Peru but with a flattening of the zone north of about 16°S.

The dip of the seismic zone is best shown by profiles. We made profiles perpendicular to the coast, and they show the same changes in dip as do those of Hasegawa and Sacks (1981). Here we show projections parallel to the direction of relative plate motion (Figure 3). Well located events in the southernmost part are sparse, but those in sections C3, C4, and C5 indicate a constant dip of 25° from near the surface to about 200 km depth. The dip of the zone decreases to about 20° in C6, 15° in C7, and 5° in C8. There is no major change in the local dip of the zone on these individual profiles as there clearly is with profiles drawn perpendicular to the coast (see Grange, 1983; Hasegawa and Sacks, 1981).

The configuration of the contortion and the direction of plate motion suggest that the contortion is not directly related to the subduction of the Nazca Ridge, because the ridge is normal to the coast. Perhaps the gentle dip of the seismic zone is a result of the buoyancy of that ridge (Barazangi and Isacks, 1979; Pilger, 1981) but the contortion apparently lies several hundred km south of the edge of the ridge. The parallelism of the contortion and the direction of relative plate motion suggests that the contorted configuration of the slab could have existed for several m.y. If the contortion were to trend northeast, it probably would migrate eastward approximately at the velocity of subduction (~100 mm/yr) and therefore southeastward at ~70 mm/yr. Moreover, by being parallel to the direction of subduction, the contortion could be approximately fixed relative to the South American plate or to the hotspot frame. Thus there is no need for material to move out of the way of the warped downgoing Nazca plate as would be required if the contortion moved. Hence, the flow in the asthenosphere associated with subduction could be in a steady state.

The configuration of the seismic zone in Figure 2 strengthens Barazangi and Isacks's (1976; 1979) inference that volcanism requires a wedge of asthenosphere between the overriding and subducting plates. Most of the active volcanoes occur where the seismic zone is between 120 and 140 km deep (Figure 1 and 2), and the line of active volcanoes stops abruptly where the slab is contorted, not 100 km northwest of that contortion as is required by the "tear" of Barazangi and Isacks (1976, 1979).

In summary, the locations presented (Figures 1-3) here corroborate Barazangi and Isacks's (1976, 1979) observation that the seismic zone dips at a gentle angle beneath central and northern Peru and more steeply beneath southern Peru. They also concur with Hasegawa and Sacks's (1981) inference that the zone is contorted and that there is no major tear in the slab. Most importantly, however, these data show that the contortion is aligned parallel to the direction

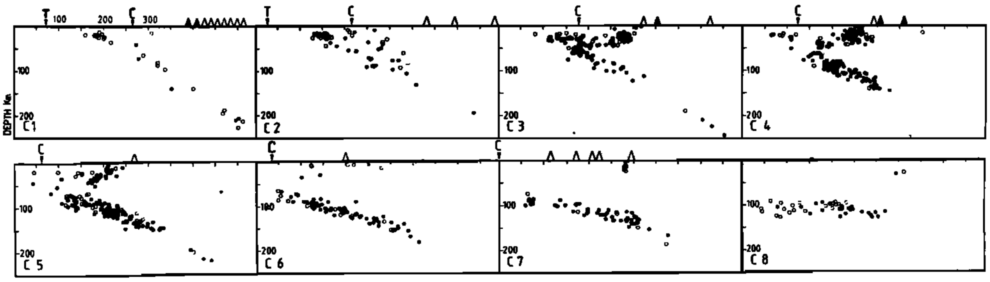

Fig. 3. Cross-sections of seismicity parallel to N80°E, the approximate trend of the contortion in the zone, as well as the direction of relative plate motion. Note this absence of any bend or change in apparent dip of the zone in each profile.

of subduction and not perpendicular to the coast. Thus, the contortion need not migrate with time but can be approximately fixed relative to the South American plate (or the hot spot reference frame). Finally, the volcanic line terminates above the contortion in the seismic zone, and there seem to be no active or recently active calc-alkaline volcanoes where the seismic zone dips at a gentle angle (0-10°) beneath Peru. Thus the data support Barazangi and Isacks's (1976, 1979) contention that the existence of volcanoes requires a wedge of asthenosphere between the overriding and underthrusting plates.

Acknowledgements. We thank O. Ancajima, C. Anconeyra, R. Benites, A. Flores, F. Gomez, J. Melgar, T. Modiano, F. Pardo, A. Posadas, E. Salinas, R. Stewart, I. Vallejos, and A. Vilkas for assistance in the field and M. Lazo, F. Mégard, M. Sebrier and J.C. Vicente for advice and help with logistics. This work was supported by NASA grant NAG5-300 of the Geodynamics Program and by an H.O. Wood award from the Carnegie Institution in Washington, D.C.

References

Barazangi, M., and B.L. Isacks, Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America, Geology, 4, 686-692, 1976.

Barazangi, M., and B.L. Isacks, Subduction of the Nazca Plate beneath Peru: evidence from the spatial distribution of earthquakes, Geoph. Jour. Roy. Astr. Soc., 57, 537-555, 1979.

Chatelain, J.L., S.W. Roecker, D. Hatzfeld, and P. Molnar, Micro-earthquake seismicity and fault plane solutions in the Hindu-Kush regions and their tectonic implications, J. Geophys. Res., 85, 1365-1387, 1980.

Carr, M.J., R.E. Stoiber, and C.L. Drake, Discontinuities in the deep seismic zones under the Japanese arcs, Bull. Geol. Soc. Amer. 84, 2917-2930, 1973.

Chen, W.P., and P. Molnar, Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, J. Geophys. Res, 88, 4183-4214, 1983.

Dalmayrac, B., G. Laubacher, and R. Marocco, Geologie des Andes Peruviennes Publication ORSTOM, 122, 1980.

Grange, F., Étude sismotectonique detaillée de la subduction lithospherique au sud Peru, These pour docteur de 3^e cycle, I.R.I.G.M., Grenoble, 1983.

Hasegawa, A. and Sacks, I.S., Subduction of the Nazca plate beneath Peru as determined from seismic observations, J. Geophys. Res., 86, 4971-4980, 1981.

Hatzfeld, D., and M. Frogneux, Intermediate depth seismicity in the western Mediterrannean unrelated to subduction of oceanic lithosphere, Nature, 292, 443-445, 1981.

Isacks, B., and P. Molnar, Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes, Rev. Geophys. Space Phys., 9, 103-174, 1971.

Isacks, B.L., J. Oliver, and L.R. Sykes, Seismology and the new global tectonics, J. Geophys. Res., 73, 5855-5899, 1968.

Klein, F.W., Hypocenter location program HYPOINVERSE: U.S. Geological Survey, Open File Report, 78-694, 1978.

Minster, B., and T.H. Jordan, The present day plate motions, J. Geophys. Res., 83, 5331-5354, 1978.

Pilger, R.H., Plate reconstructions, aseismic ridges, and low angle subduction beneath the Andes, Geol. Soc. Amer. Bull., Part I, 92, 448-456, 1981.

Roecker, S.W., Velocity structure of the Pamir-Hindu Kush region; Possible evidence of subducted crust, J. Geophys. Res. 87, 945-960, 1982.

Sykes, L.R., Seismicity and deep structure of island arcs, J. Geophys. Res., 71, 2981-3006, 1966.

(Received October 3, 1983;
accepted October 4, 1984.)