

*MORPHOLOGY OF THE WADATI-BENIOFF ZONE AND VOLCANISM
IN ECUADOR AND NORTHERN PERU*

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RESUMEN

Se identificaron la morfología y los parámetros de la zona de Wadati-Benioff con base en la distribución de los focos de terremotos en la región de Ecuador y del norte de Perú. Se confirmó la existencia de una zona asísmica de profundidad intermedia relacionada con los volcanes andesíticos activos en Ecuador y en el sur de Colombia. En la zona de subducción de inclinación moderada se encontró una región asísmica que se correlaciona con el volcanismo pliocénico y pleistocénico en el norte de Perú y en el sur de Ecuador. La profundidad variable de la penetración y la segmentación posible de la zona de subducción parece relacionarse con el efecto de frenaje de las elevaciones principales y de las zonas fracturadas de la placa de Nazca. Se calculó la velocidad promedio de la subducción y el tiempo del comienzo del ciclo presente de la subducción andina.

ABSTRACT

The morphology and parameters of the Wadati-Benioff zone were established on the basis of the distribution of earthquake foci in Ecuador and northern Perú. The existence of an intermediate depth aseismic gap related to active andesitic volcanoes was confirmed in Ecuador and southern Colombia. For the flatly inclined slab an aseismic region in the Wadati-Benioff zone was found and correlated with the occurrence of the Pliocene and Pleistocene volcanism in northern Perú and southern Ecuador. The laterally variable depth of penetration and possible segmentation of the subduction zone appeared to be connected with the hampering effect of major ocean floor elevations and fracture zones of the Nazca plate. The mean rate and the time of beginning of the present cycle of the Andean subduction were estimated.

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INTRODUCTION

The equatorial part of Andean South America seems to be one of the most complicated regions for a plate tectonic interpretation of its deep structure and geological evolution. The region is characterized by a flatly inclined Wadati-Benioff zone with absence of active volcanoes in northern Perú and southern Ecuador (Stauder, 1975; Barazangi and Isacks, 1979), by a relatively high seismicity in the overlying wedge of the South American plate (Stauder, 1975; Barazangi and Isacks, 1979), and by a clustering of intermediate depth earthquakes in several parts of the Wadati-Benioff zone (Santô, 1969).

Several authors have recently investigated the above phenomena in connection with further tectonic, geological and geophysical evidence (Sacks, 1977, 1983; Barazangi and Isacks, 1979; Pennington, 1981; Suárez *et al.*, 1983; Hall and Wood, 1985) without succeeding to reach a generally acceptable solution in the framework of plate tectonic concepts. It seems that further work based on actual observations would be very desirable.

The aim of the present paper is to re-investigate the detailed geometrical distribution of earthquake foci in order to define the shape and morphology of the Wadati-Benioff zone in the region, to correlate it with the distribution of volcanism, and to delineate, where possible, seismically active fracture zones in the continental wedge.

MATERIALS

For the construction of the Wadati-Benioff zone and for the delineation of the seismically active fracture zones in the region of Ecuador and northern Perú, the ISC data (Regional Catalogue of Earthquakes) for the period 1964-80 were used as basic material. All determinations with lower accuracy, characterized by errors greater than 0.2° in epicentral co-ordinates, were rejected. This basic material was complemented by data of NEIS (Preliminary Determination of Epicenters) for 1981-83. Altogether a set of 1588 earthquakes was used in the present study.

The region of northern Perú was covered by a system of 13 parallel sections, perpendicular to the axis of the Perú-Chile trench (sections L1-L13 in Fig. 1) and by a triangular section L14, the region of northernmost Perú and Ecuador by a system of

11 parallel sections (sections E1-E11 in Fig. 1) and by a triangular section N1 reaching the southern part of Colombia. The area under investigation is limited by a line between 2.5°N , 79.5°W and 0° , 76°W in the north, and by a line between 15°S , 77°W and 10.5°S , 71°W in the south.

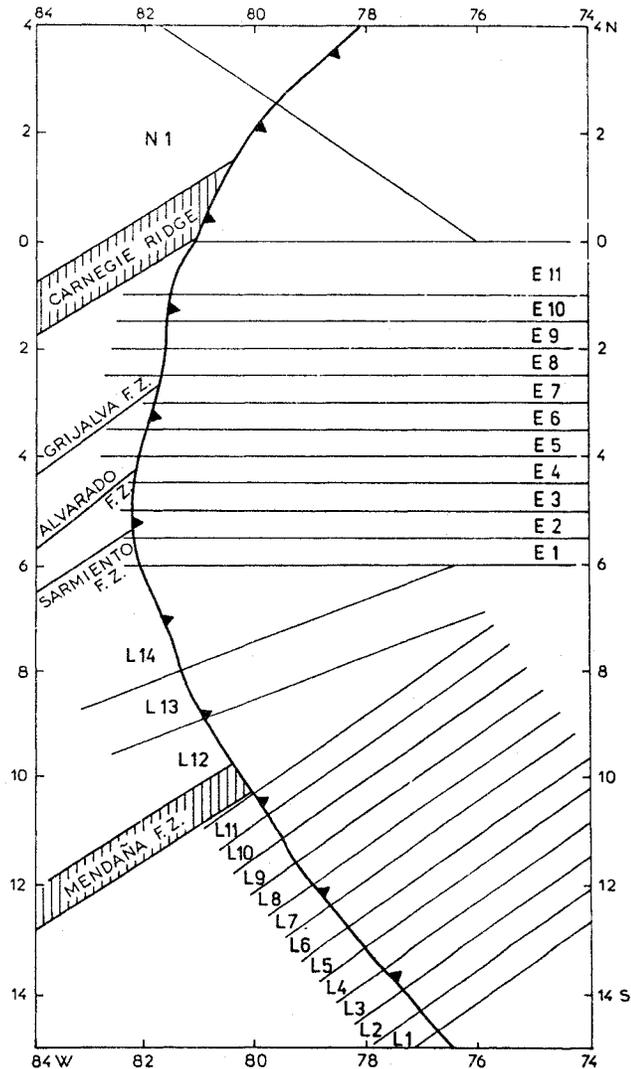


Fig. 1. Main structural elements of the Nazca plate and scheme of sections used for the study of the Wadati-Benioff zone in Ecuador and northern Perú; the Perú-Chile trench is denoted by a serrated line.

The general picture of seismicity was obtained by constructing a graph of the Wadati type (Wadati, 1935) plotting the epicenters of shallow, intermediate and deep earthquakes on a suitable geographic map. This map of epicenters helped us to construct the appropriate scheme of cross sections with a reasonable density of earthquake foci. The map of this type also appeared to be very useful for the study of the morphology of the Wadati-Benioff zone in the region of the flatly inclined slab. The graphs giving the depth distribution of earthquake foci in dependence on the distance from the trench axis, constructed for every section, as well as the longitudinal section along the trench complemented the general picture of the earthquake distribution in the region investigated.

The main source of volcanological data was the Catalogue of the Active Volcanoes of the World (Hantke and Parodi, 1966) completed by the work of Simkin *et al.* (1981), especially in Holocene volcanic activity, and by data in the respective geological maps (Mapa geológico de la República del Ecuador, 1969, 1982; Mapa geológico del Perú, 1975; Cobbing *et al.*, 1981) for Pliocene and Pleistocene volcanism.

Necessary bathymetric data in the region investigated were taken from the bathymetric charts and graphs published in Mammerickx *et al.* (1975), Yeats, Hart *et al.* (1976), Honnorez, Von Herzen *et al.* (1983), and Lonsdale and Klitgord (1978). Basic tectonic information was obtained from the Tectonic Map of South America (1978), from Fiedler and González-Ferrán (1983), and from the geological maps of Ecuador and Perú (Mapa geológico de la República del Ecuador, 1969, 1982; Mapa geológico del Perú, 1975; Cobbing *et al.*, 1981).

Deep-focus earthquakes occurring between the parallels 8° - 14° S were not included into the present study; they are shifted westwards and do not probably belong to the present subduction zone (Hanusš and Vaněk, 1978).

VERTICAL SECTIONS ACROSS THE TRENCH

The depth distribution of earthquake foci in relation to the distance from the Perú-Chile trench axis is given in Figs. 2-10. For easier understanding of the spatial correlation of different phenomena with the morphology of the Wadati-Benioff zone, the positions of the axis of the Perú-Chile trench (arrows), active volcanoes (full triangles), the Pliocene and Pleistocene volcanism in Perú and southern Ecuador (heavy vertical and horizontal lines for small and areal occurrences, respectively) are

shown in the upper part of the graphs; our delineation of the Wadati-Benioff zone is denoted by heavy parallel lines in every graph. The position of the seismically active fracture zones in the continental wedge is also given in sections E1-E11.

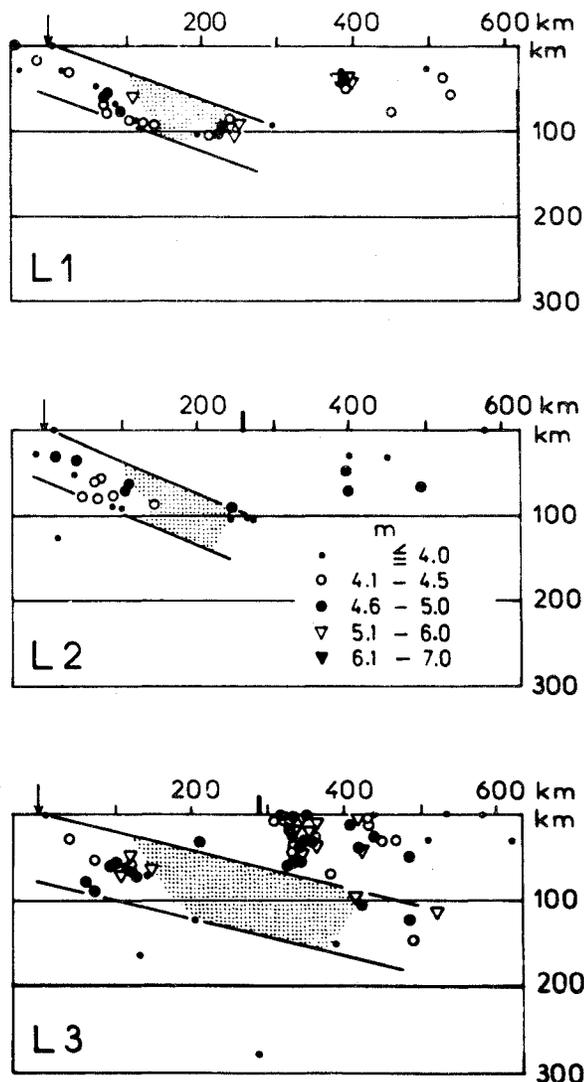


Fig. 2. Vertical sections L1, L2, L3 giving the depth distribution of earthquake foci in relation to their distance from the trench; m = ISC magnitude; active volcanoes are denoted by triangles, Pliocene and Pleistocene volcanism in Perú and southern Ecuador by heavy vertical and horizontal lines for small and areal occurrences, respectively, position of the trench axis by an arrow, foci of NEIS by crosses, Wadati-Benioff zone by heavy parallel lines, and aseismic region by a dotted area. Position of sections shown in Fig. 1.

The general picture shown by the sequence of vertical sections confirms the existence of a well-defined Wadati-Benioff zone beginning in the vicinity of the Perú-Chile trench. The dip of the zone abruptly changes between sections L2 and L3, decreasing from 20° - 24° in the southernmost sections L1, L2 to 12° - 15° in sections L3-L14. This flatly inclined subduction appears to continue in the sequence of sec-

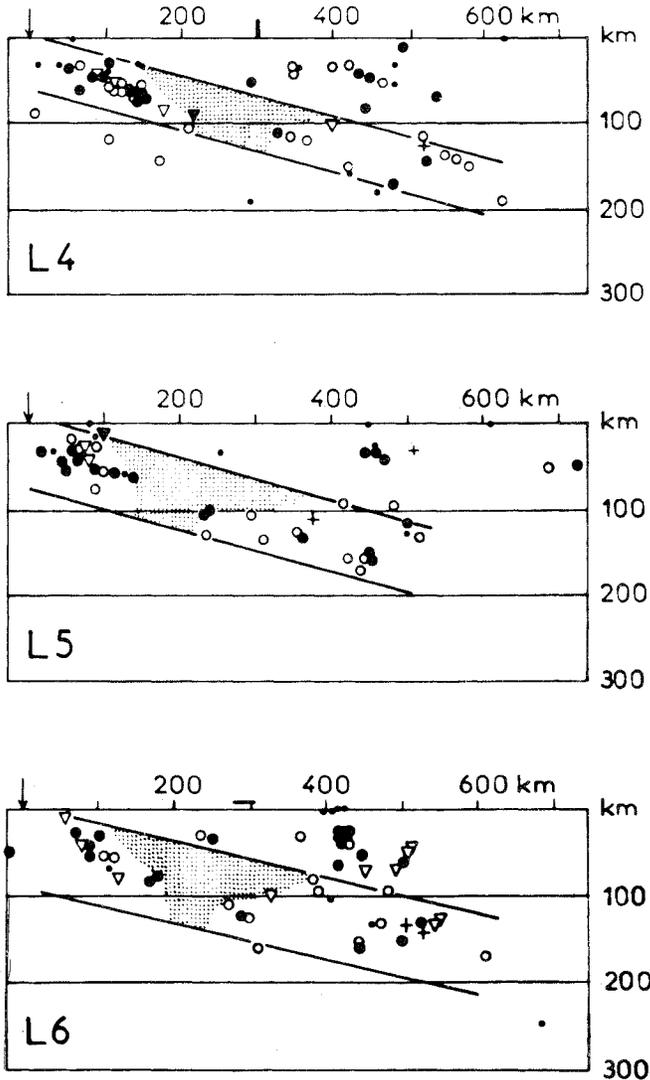


Fig. 3. Vertical sections L4, L5, L6. For key see Fig. 2.

tions E1-E8 where the dip varies between 12° and 16° . The dip abruptly increases to 23° - 20° in the northern sections E9-E11 and attains more than 40° in the Colombian section N1. The distribution of earthquake foci in the whole sequence of **vertical** sections shows that the subducted Nazca plate does not change dip with depth during its penetration. It appears that the change of inclination of the slab to

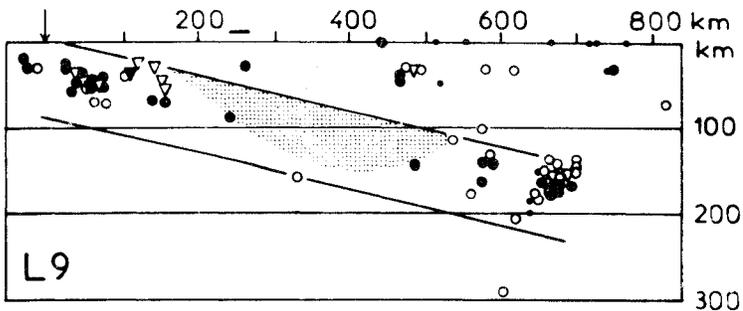
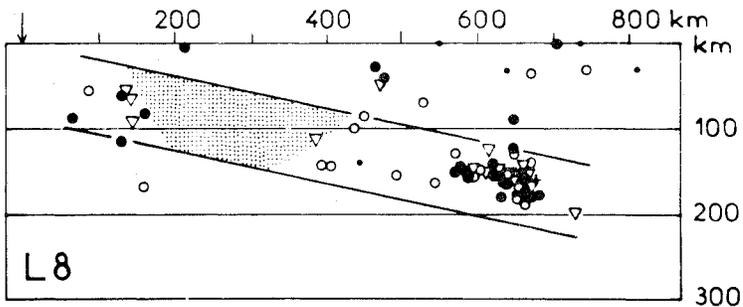
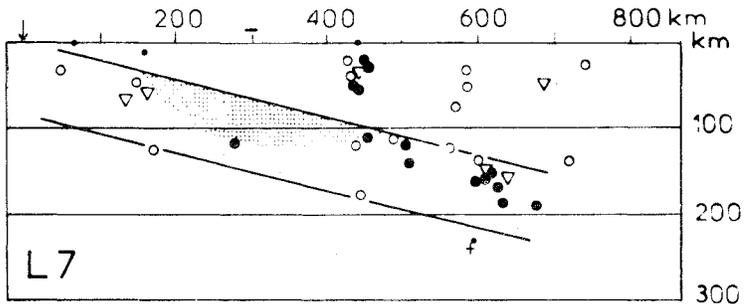


Fig. 4. Vertical sections L7, L8, L9. For key see Fig. 2.

horizontal direction in a certain part of the subducted plate, described by Hasegawa and Sacks (1981) in Central Perú, is not favoured by the observed distribution of earthquakes north of 14°S . However, the increasing dip of the slab observed in sections L1 and L2 might indicate the transition to the shape with depth-variable inclination of the subduction zone found in Central Perú by means of local networks

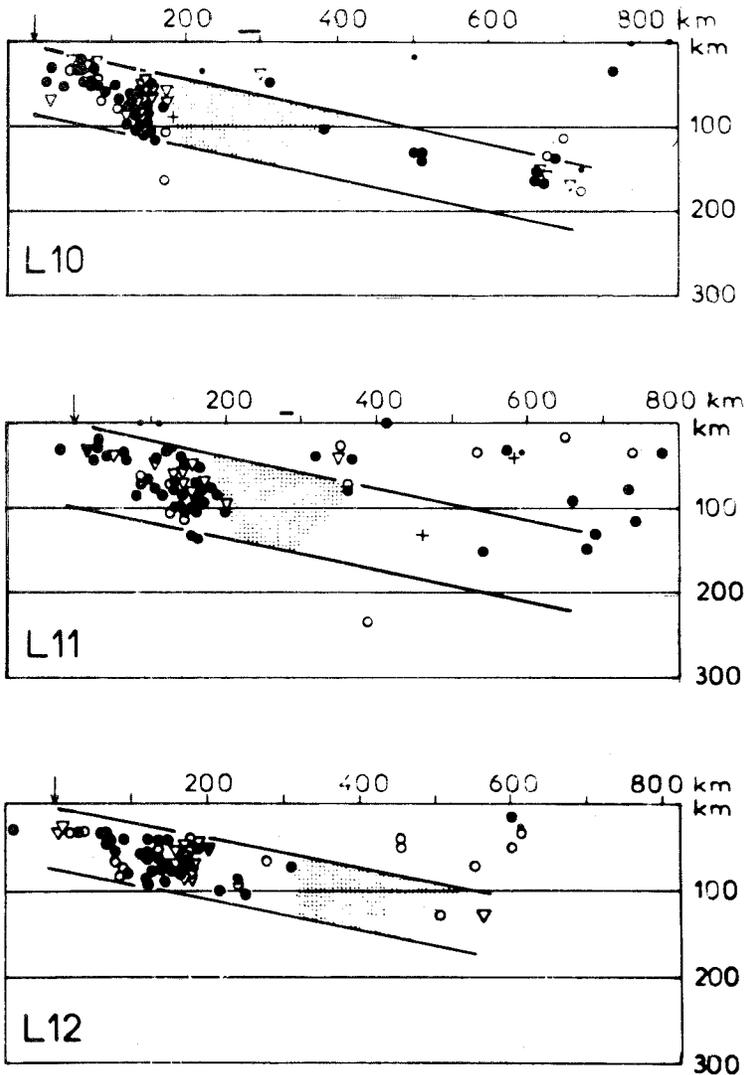


Fig. 5. Vertical sections L10, L11, L12. For key see Fig. 2.

of stations (Hasegawa and Sacks, 1981; Sacks, 1983; Grange *et al.*, 1984). It is remarkable that sections L1 and L2 are situated near the northern border of the Nazca Ridge, the subduction of which might be the main cause of the anomalous shape of the slab observed in Central Perú (Sacks, 1983).

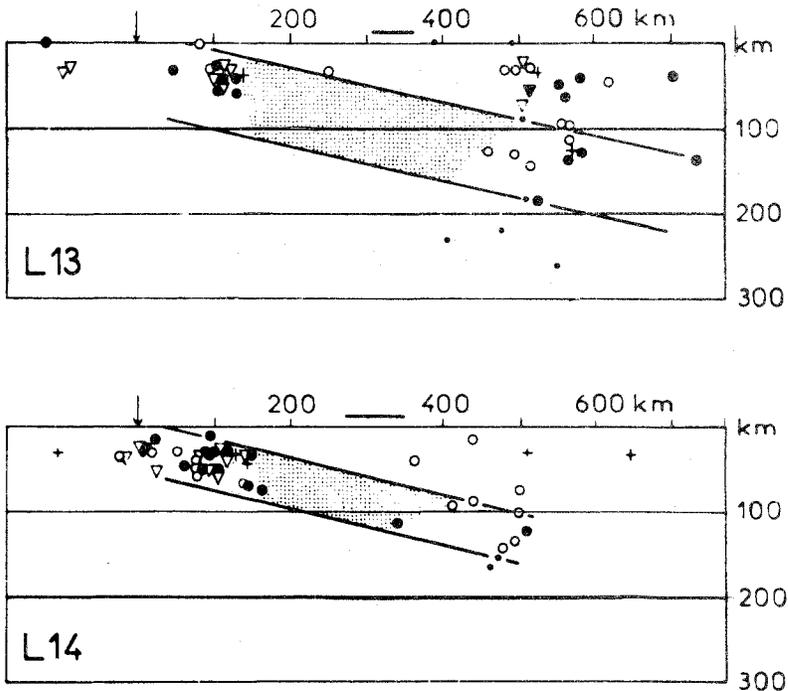


Fig. 6. Vertical sections L13, L14. For key see Fig. 2.

The thickness of the Wadati-Benioff zone, measured perpendicularly to the direction of subduction, varies between 40 and 95 km with prevailing values between 60 and 90 km. The maximum depth of earthquake foci in individual sections varies considerably between 105 km (section L2) and 225 km (section E9). The variation of the length of the slab, measured from the trench axis in the direction of subduction, is even more expressive. The maximum length of the slab is observed in the flatly inclined part of the subduction zone in the continuous sequence of sections between L3 and E8. Omitting minor fluctuations (L3, L5, L12, L14), the length of this part of the subduction zone is more than 600 km with the maximum value of 780 km (section E1). In sections with larger inclination of the slab the length of the active part of the subduction zone is considerably smaller, decreasing down to 260-290 km (sections N1, L2).

The specific distribution of earthquakes within the Wadati-Benioff zone manifests the existence of an extensive region without occurrence of any foci in almost all the vertical sections (see dotted area in Figs. 2-10). A similar phenomenon was observed in the subduction zones of other Pacific convergent plate margins and the region without earthquake foci was denoted as intermediate depth aseismic gap (Hanuš and Vaněk, 1976, 1977-78, 1978, 1979ab, 1983, 1984); the aseismic gap probably re-

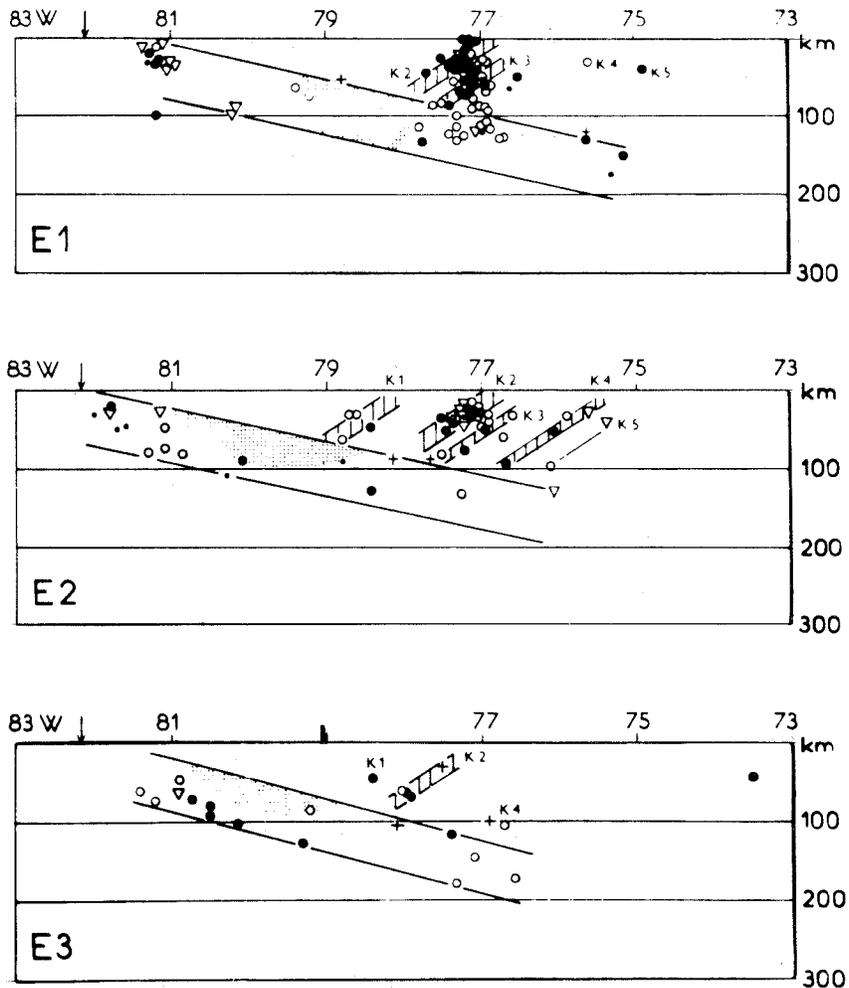


Fig. 7. Vertical sections E1, E2, E3. Fracture zones in the continental plate are denoted by symbols and hatching. For key see Fig. 2.

presents the partially melted part of the subduction zone, the state conditions for its occurrence being governed by the depth of penetration of the slab. It appears that for the flatly inclined subduction zone, observed in northern Perú and southern Ecuador, the occurrence of the aseismic part of the Wadati-Benioff zone does not

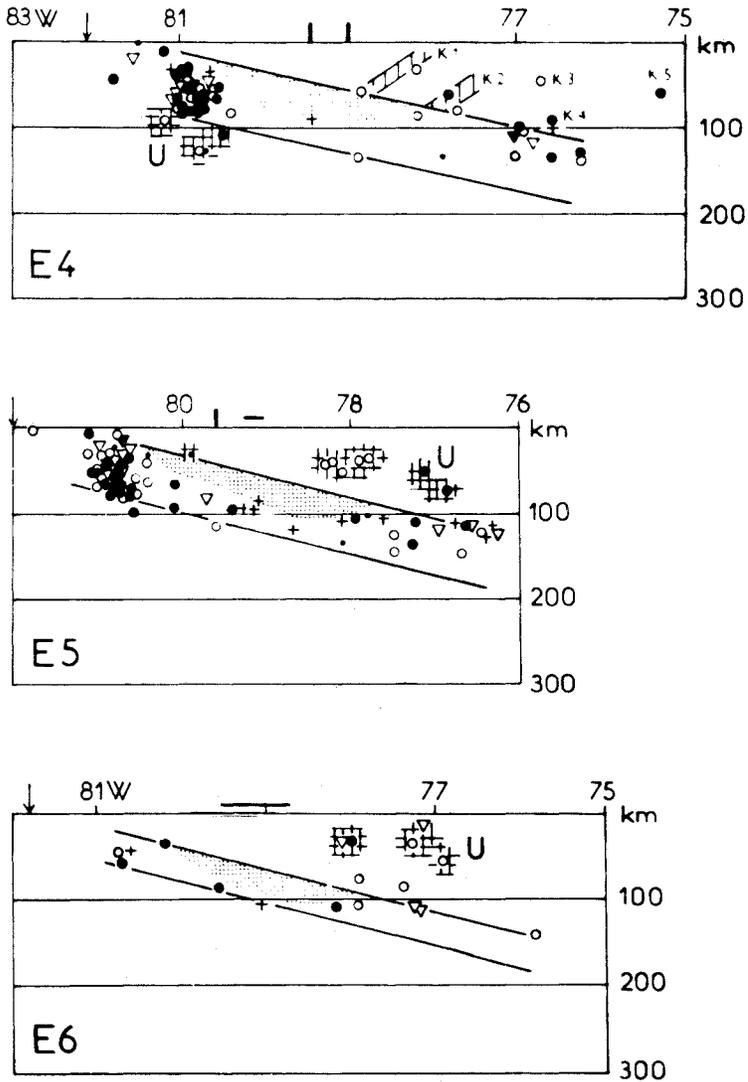


Fig. 8. Vertical sections E4, E5, E6. For key see Figs. 2 and 7.

depend only on the depth of penetration but that the conditions, favourable for its existence, seem to be influenced, first of all, by the distance from the trench. Moreover, in several sections the aseismic region does not cover the whole thickness of the slab, being observed only in its upper part (see sections L7, L9, E2-E7).

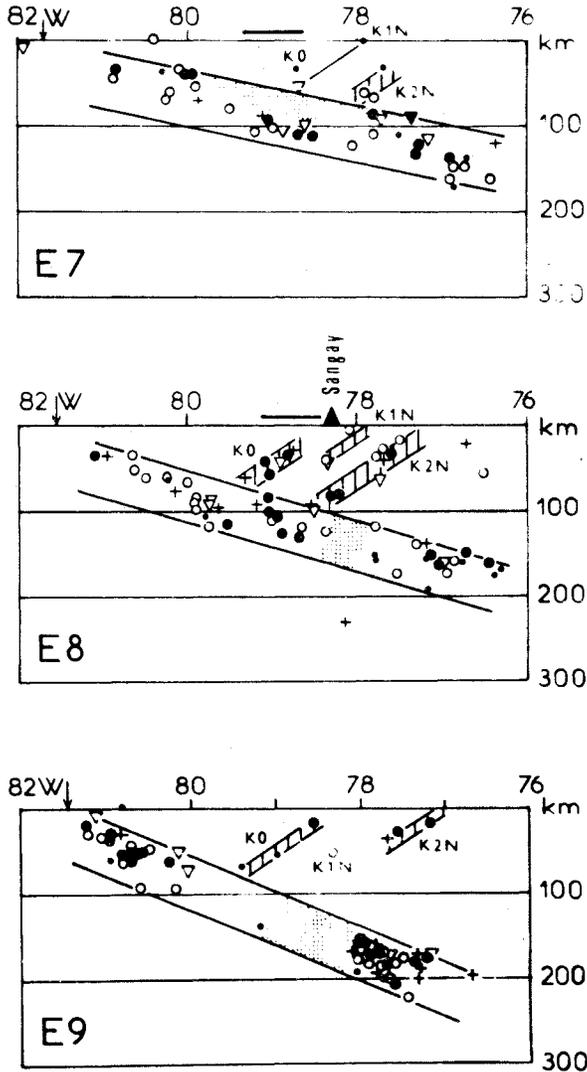


Fig. 9. Vertical sections E7, E8, E9. For key see Figs. 2 and 7.

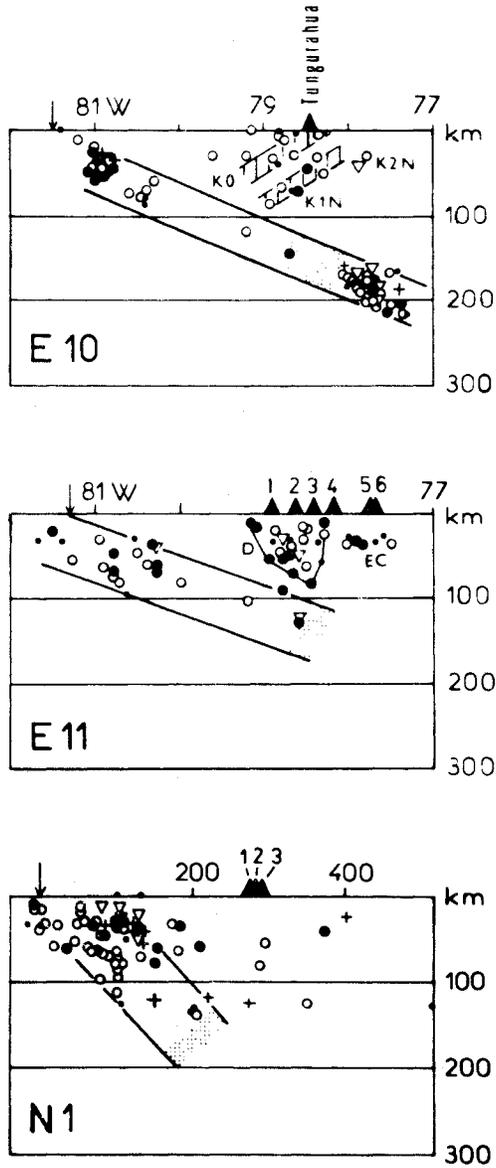


Fig. 10. Vertical sections E10, E11, N1. Volcanoes in E11: 1 - Quilotoa, 2 - Pichincha, 3 - Cotopaxi, 4 - Antisana, 5 - Reventador, 6 - Sumaco; in N1: 1 - Cumbal, 2 - Mayasquer, 3 - Túquerres. For key see Figs. 2 and 7.

The depth of the upper limit of the aseismic region varies between 25 and 60 km with prevailing values between 25 and 40 km. The deepest extension of the aseismic region varies between 90 and 160 km with prevailing depths of 140-160 km in northern Perú and 90-105 km in southern Ecuador. In northern Ecuador, where the dip of the slab increases and active andesitic volcanism occurs, the aseismic gap starts in the depth of 100-130 km and can be observed down to 200 km (see sections E8-E11, N1).

As stated above, the distance from the trench axis, measured along the slab, may be an important parameter for flatly inclined subduction zones. The distance of the beginning of the aseismic region from the trench axis varies in individual sections between 110 and 320 km with prevailing values of 150-175 km; the aseismic region reaches the distances between 245 and 520 km with prevailing values of 400-450 km. The length of the aseismic region fluctuates between 135 and 355 km with prevailing values of 275-300 km. These fluctuations seem to manifest lateral variations of state conditions in the subduction zone along the trench.

It should be noted that no active volcanism is observed above the flatly inclined zone of subduction; the occurrence of the Pliocene and Pleistocene volcanism, connected with the process of recent subduction, will be discussed later.

VERTICAL SECTION ALONG THE TRENCH

The sequence of vertical sections in Figures 2-10 indicates that the maximum depth of penetration of the active subducted plate varies along the Perú-Chile trench. It was shown in our previous papers on Andean South America, Tonga-Kermadec and Vanuatu island arcs (Hanus and Vaněk, 1978, 1979a, 1983) that such a lateral variability was probably caused by the hampering effect of main structural units of the subducting oceanic plate. In order to correlate the morphology of the subduction zone in northern Perú and Ecuador with the physiography of the Nazca plate, a vertical section of the Wadati-Benioff zone along the Perú-Chile trench was constructed in Figures 11-13. In this section all the earthquake foci belonging to the subduction zone are plotted, allowing us to contour the lower limit of the Wadati-Benioff zone in the whole region and the position of the intermediate aseismic gap in sections E8-E10. The positions of active andesitic volcanoes are also indicated in the upper part of Figure 13.

The scheme of main structural elements of the respective part of the Nazca plate

is given in Figure 1. The following units characterized by elevations of the ocean floor and tectonic fractures can be distinguished from south to north in the region investigated: Mendaña fracture zone, Sarmiento fracture zone, Alvarado fracture zone, Grijalva fracture zone, and Carnegie Ridge. The position of the above units is also indicated in Figures 11-13.

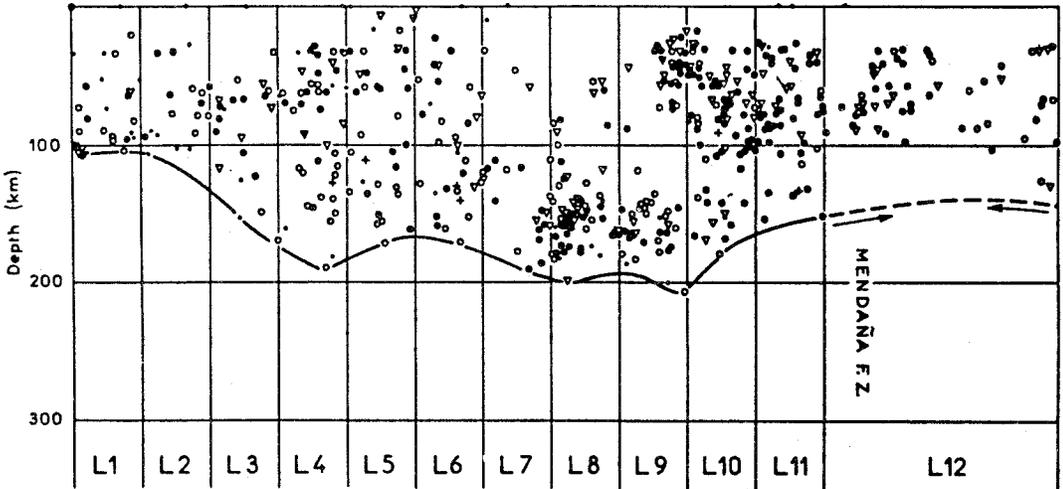


Fig. 11. Detailed morphology of the Wadati-Benioff zone in northern Perú (sections L1-L12). Earthquake foci, denoted as in Fig. 2, are projected onto a vertical plane in the axis of the Perú-Chile trench; contour of the lower limit of the Wadati-Benioff zone is given by a solid line; the section of irregular shape L12 shows an apparent widening of the longitudinal section in intermediate depths, as indicated by two opposite arrows.

The longitudinal section shows that the subduction of the Nazca plate is manifested not only by a decreased depth of penetration but also by an interruption of seismic activity in the vicinity of several above mentioned tectonic units. The seismic activity seems to be interrupted in linear belts running across the whole subduction zone; the width of these belts varies between 20 and 30 km. These belts might be interpreted as weakened parts of the subducted slab where differential movements are compensated by possible plastic flow. This phenomenon may point to a segmentation of the subduction zone along the Perú-Chile trench, which in the region of Perú, Ecuador and Colombia changes its strike several times (Fig. 1). However, there is no evidence for a drastic change in the direction of subduction in sections E9 and E10 as claimed by Pennington (1981). The problem of the possible segmentation of the Andean subduction zone will be treated in a special paper in relation to the segmentation of the overlying continental plate (Hall and Wood, 1985).

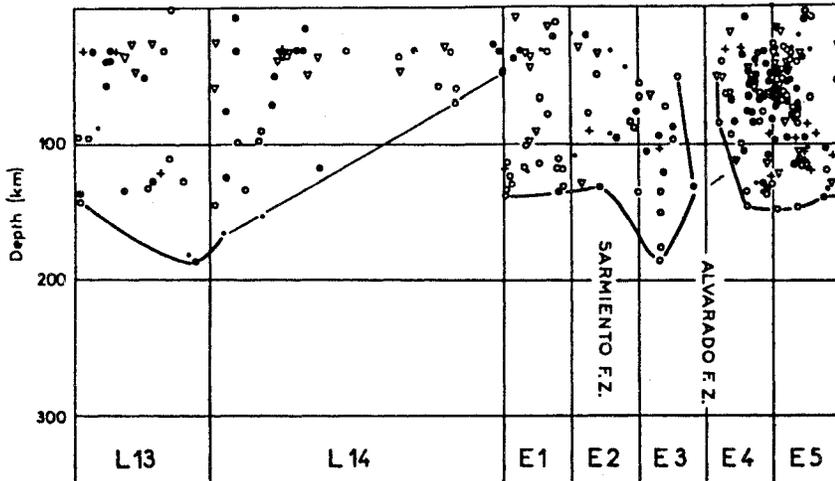


Fig. 12. Detailed morphology of the Wadati-Benioff zone in northern Perú and southern Ecuador (sections L13, L14, E1-E5). The triangular section L14 shows an apparent widening of the longitudinal section, as indicated by a thin line. For key see Fig. 11.

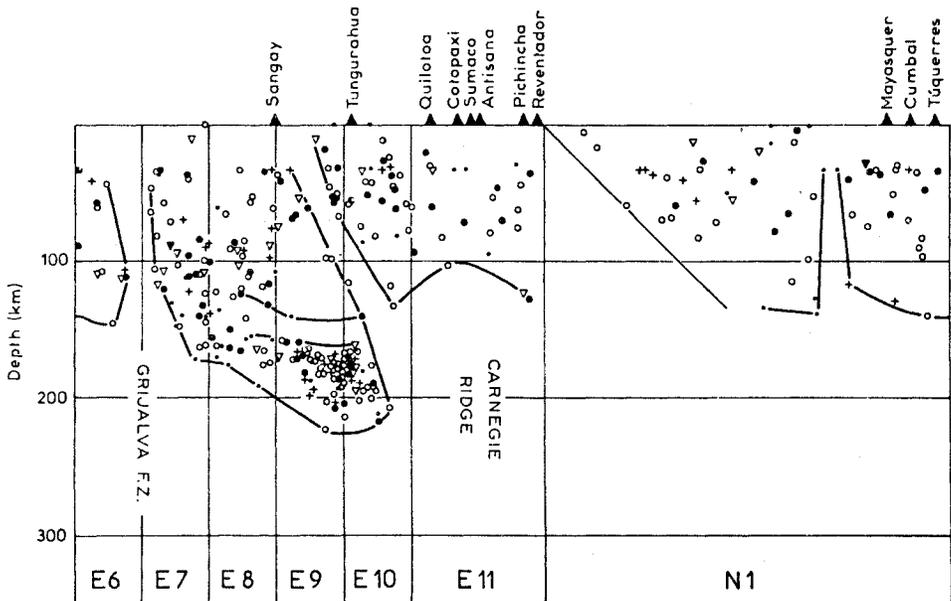


Fig. 13. Detailed morphology of the Wadati-Benioff zone in Ecuador and southern Colombia (sections E6-E11, N1). Active volcanoes are denoted by full triangles in the upper part of the graph. The triangular section N1 shows an apparent widening of the longitudinal section, as indicated by a thin line. For key see Fig. 11.

The intermediate depth aseismic gap could be delineated only in sections E8-E10, where active volcanoes Sangay and Tungurahua also occur. In the region of northern Ecuador and southern Colombia the seismic activity enabled us to draw only the upper limit of the aseismic gap, the existence of which can be anticipated from the occurrence of active andesitic volcanism (see sections E11 and N1). This would indicate that the subducted slab has not penetrated yet beneath the lower limit of the aseismic gap (compare, e.g., a similar phenomenon in the region of the Vanuatu island arc described in Hanuš and Vaněk, 1983).

The aseismic region observed in the vertical sections of the flatly inclined subduction zone (Figs. 2-10) does not appear in the longitudinal section given in Figures 11-13 due to the small dip of the subducted slab. A more suitable representation for the study of lateral variations of this aseismic region is a projection of earthquake foci to a horizontal plane, which is discussed in the following paragraph.

MAP OF EPICENTERS

In order to study the morphology of the Wadati-Benioff zone in the region of the flatly inclined slab, the vertical sections across and along the trench were complemented by a map of epicenters (Figs. 14, 15, 16). This map, containing only epicenters of earthquakes belonging to the subduction zone, enabled us to delineate the aseismic region of the Wadati-Benioff zone in sections L1-L14, E1-E7 and the intermediate aseismic gap in the northern sections E8-E10. The aseismic region forms a belt without earthquakes expressed by full-line contours in the map; 20 epicenters located within this belt between the parallels 9° - 12° S and 2.5° - 4° S are from the lower part of the subduction zone in the places where the aseismic region does not cover the whole thickness of the slab. The aseismic region can be clearly traced from 14° S to 2.5° S where an abrupt increase of the dip of the slab occurs and where the intermediate aseismic gap in the Wadati-Benioff zone starts to be observed.

The width of the aseismic region varies laterally between 60 and 340 km. The maximum length of the subduction zone, constructed on the basis of the most distant earthquakes from the trench, manifests also a considerable lateral variation in the extent of penetration of the subducted slab.

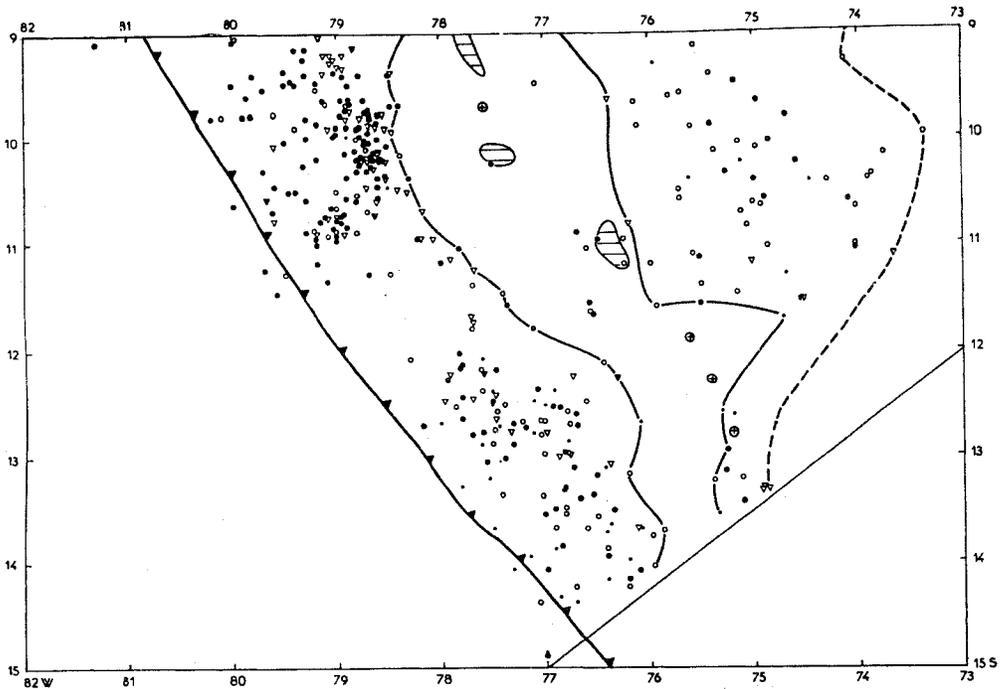


Fig. 14. Map of epicenters of earthquakes belonging to the Wadati-Benioff zone in northern Perú. Epicenters are denoted by symbols as in Fig. 2. The Perú-Chile trench is denoted by a serrated line, limits of the surface projection of the aseismic region by full-line contours and the limit of the most distant epicenters from the trench by a dashed contour. Outcrops of the Pliocene and Pleistocene volcanics are denoted by circled crosses for individual and by hatched fields for areal occurrences, respectively.

CORRELATION WITH VOLCANISM

Active volcanism in the region investigated is limited to its northern part starting at 2°S and continuing through Ecuador to Colombia. The list of active and Quaternary volcanoes of Ecuador and southern Colombia, compiled in collaboration with M. Hall (Escuela Politécnica Nacional, Quito), is given in Table 1 (compare also Hall, 1977). The rocks produced belong to the calc-alkaline volcanic series (Hantke and Parodi, 1966). The position of volcanoes is also plotted in Figure 16. By combining all the projections of earthquake foci (Figs. 9, 10, 13 and 16) all these volcanoes appear to occur above the intermediate aseismic gap of the Wadati-Benioff zone. The apparent unconformity in vertical section E11 is caused by a strong lateral variability of the upper limit of the gap (compare Fig. 16). The active volcanoes Sumaco

and Reventador are shifted about 50 km to the east; it is not excluded that their position is influenced by a deeply seated fracture zone, which is observed in the continental wedge (Santa Helena-Santa Cecilia fracture zone CS in Hanuš and Vaněk, 1987).

Table 1
Active and Quaternary volcanoes of Ecuador and southern Colombia
(A - active, Q - Quaternary)

No.	Volcano	Co-ordinates		Remark
1	Sacra Urcu	2.02S	78.55W	Q
2	Sangay	2.00S	78.35W	A
3	Chanlor	1.96S	78.82W	Q
4	Pan de Azúcar	1.95S	78.57W	Q
5	Nevado Altar	1.67S	78.43W	Q
6	Igualata	1.49S	78.66W	Q
7	Nevado Chimborazo	1.47S	78.82W	Q
8	Tungurahua	1.45S	78.45W	A
9	Carihuayrazu	1.38S	78.76W	Q
10	Sagoatoa	1.12S	78.67W	Q
11	Quilotoa	0.86S	78.98W	A
12	Quilindaña	0.75S	78.31W	Q
13	Cotopaxi	0.68S	78.44W	A
14	Iliniza	0.65S	78.72W	Q
15	Rumiñahui	0.60S	78.53W	Q
16	Sumaco	0.54S	77.62W	A
17	Sincholagua	0.53S	78.37W	Q
18	Corazón	0.52S	78.66W	Q
19	Nevado Antisana	0.50S	78.14W	A
20	Pasochoa	0.47S	78.47W	Q
21	Atacazo	0.35S	78.62W	Q
22	Ilalo	0.25S	78.42W	Q
23	Puntas	0.20S	78.20W	Q
24	Pichincha	0.16S	78.55W	A
25	Reventador	0.06S	77.67W	A
26	Calacalí	0.02S	78.50W	Q
27	Nevado Cayambe	0.03N	77.98W	Q
28	Pululagua	0.05N	78.48W	Q
29	Imbabura	0.25N	78.19W	Q
30	Cuicocha	0.30N	78.37W	Q
31	Nevado Cotacachi	0.36N	78.36W	Q
32	Yanaurcu	0.48N	78.35W	Q
33	Negro de Mayasquer	0.80N	77.95W	A
34	Cumbal	0.98N	77.88W	A
35	Azufra de Túquerres	1.08N	77.73W	A

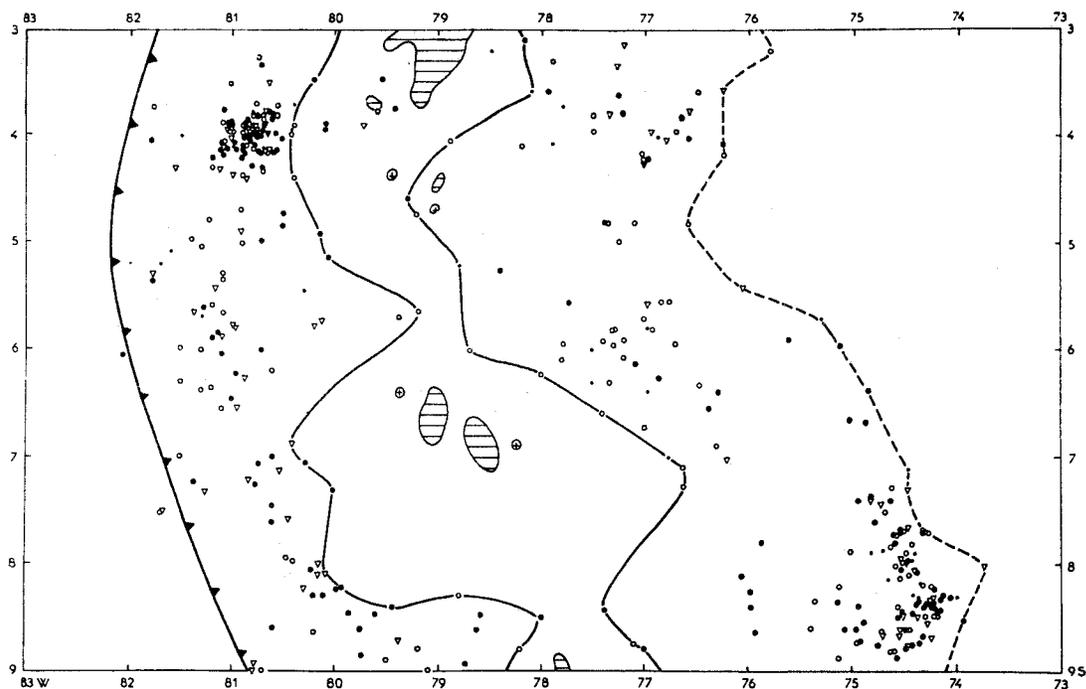


Fig. 15. Map of epicenters of earthquakes belonging to the Wadati-Benioff zone in northern Perú and southern Ecuador. For key see Fig. 14.

If we assume that the intermediate aseismic gap represents the partially melted region of the subduction zone and may serve as a source of primary magma for calc-alkaline volcanism, the depth of the supposed generation of primary magma is laterally variable (Fig. 13). In the following, the corresponding depth ranges for individual active volcanoes are given: Sangay (135-155 km), Tungurahua (140-160 km), Quilotoa (>110 km), Cotopaxi, Sumaco and Antisana (>100 km), Pichincha and Reventador (>120 km), Mayasquer (>130 km), Cumbal (>135 km), Túquerres (>140 km).

No active volcanism is observed in southern Ecuador and northern Perú between the parallels 2°S and 14°S . However, several formations of the Pliocene and Pleistocene volcanic rocks occur in this area: Formación Tarquí, between 2.0°S and 4.7°S (pyroclastics and rhyodacitic lavas of Pleistocene age denoted as P_T in Mapa Geológico Nacional de la República del Ecuador, 1982); Formación Huambos, between 6.4°S and 7.1°S (tuffs denoted as TsQ -vs in Mapa Geológico del Perú, 1975, see also Cobbing *et al.*, 1981); Formación Yungay, between 8.9°S and 9.7°S (ignimbrites,

K-Ar ages 6.2 ± 0.2 Ma, 7.6 ± 0.2 Ma in Cobbing *et al.*, 1981); Formación Fortaleza, between 10.1°S and 10.2°S (ignimbrites, K-Ar age 5.8 ± 0.2 Ma in Cobbing *et al.*, 1981; Formación Bosque de Piedras, between 10.8°S and 11.2°S (ignimbrites, K-Ar age 6.2 ± 0.2 Ma in Cobbing *et al.*, 1981, and 5.2 Ma in Farrar and Noble, 1976); three minor occurrences near 11.9°S , 12.3°S and 12.8°S (denoted as TsQ-vs in Mapa Geológico del Perú, 1975).

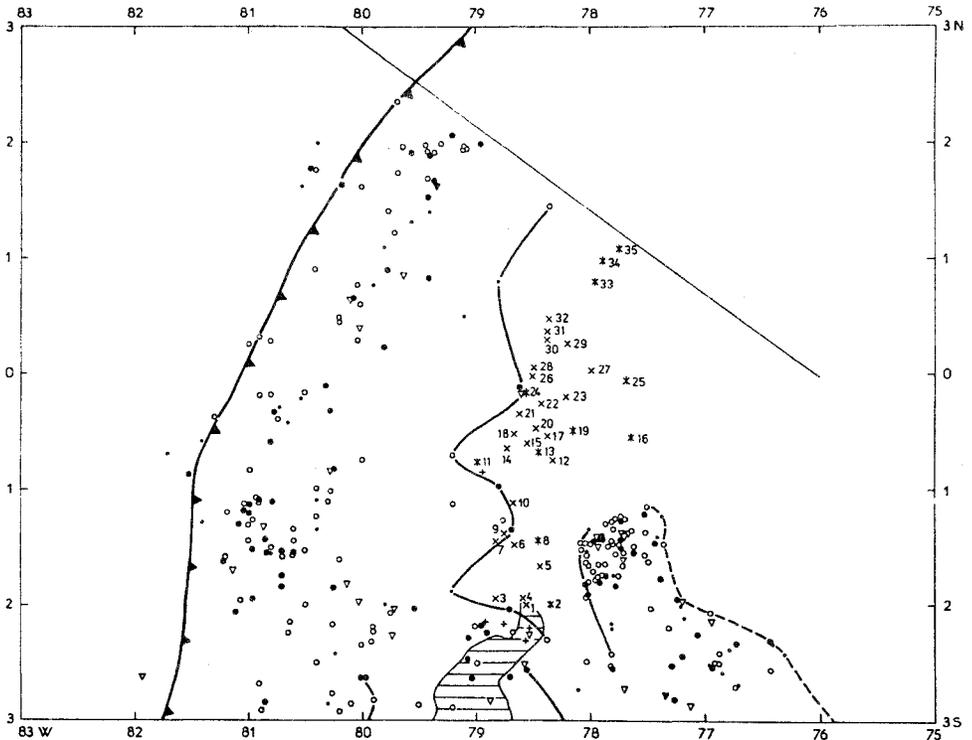


Fig. 16. Map of epicenters of earthquakes belonging to the Wadati-Benioff zone in Ecuador and southern Colombia. Active volcanoes are denoted by asterisks, Quaternary volcanoes by x's. For key see Fig. 14 and for numbering of volcanoes see Table 1.

The location of the above formations is plotted in vertical sections (Figs. 2-9) and on the map of epicenters (Figs. 14-16). It appears that practically all the volcanic bodies are situated in the belt of the surface projection of the aseismic region observed in the Wadati-Benioff zone. This fact seems to manifest a close relation of the volcanism in question with the recent process of subduction. The volcanism, which probably started in late Miocene, gradually ceased and, with a few exceptions

(Hall and Calle, 1982), shows no activity in the last few million years. However, it undoubtedly belongs to the present cycle of subduction. In analogy with the function of the intermediate depth aseismic gap, the aseismic region in the flatly inclined subduction zone may be the main reason of generation of calc-alkaline volcanic products occurring in northern Perú and southern Ecuador. The most difficult problem is to explain the cessation of volcanic activity in spite of the continuing existence of the aseismic region. It seems that the flat inclination of the slab, the considerable thickness of the continental crust and the possible absence of mantle material in the wedge (Sacks, 1983) may cause this peculiar behaviour of volcanic activity in this region. Taking into account the prevailing acid character of the volcanic rocks and probable contact of the subduction zone with the continental crust, it is not excluded that the main source of primary magma might be in this case the material of the lower crust activated by volatile components from the aseismic part of the subduction zone, the irreplaceable character of the crustal source material being the reason of the limited time span of active volcanism.

Assuming that the volcanism of northern Perú and southern Ecuador is genetically connected with the aseismic region in the subduction zone, we can roughly estimate the mean rate of subduction from the age of volcanism, from its position in relation to the slab, and from the present total length of the subduction zone. If the length of the subduction zone at the age of volcanism is estimated by vertical projection of the position of individual volcanic occurrences, the mean rate of subduction varies between 5.2 and 7.8 cm/yr (Yungay, 5.2-7.4 cm/yr, Fortaleza, 7.4-7.8 cm/yr, Bosque de Piedras, 5.2-6.7 cm/yr). The average rate of subduction is 6.3 cm/yr in the period from 8 Ma up to present. This value is in good agreement with the supposed absolute motion rate of the Nazca plate (Minster and Jordan, 1978). If we suppose that the mean rate of subduction did not drastically change before 8 Ma, we can date the beginning of the present cycle of subduction to Upper Miocene (Styrian [Quechua]? orogenic event).

CONCLUSIONS

The main results of the investigation into the geometry of distribution of earthquake foci in the Wadati-Benioff zone of Ecuador and northern Perú can be summarized in the following six points:

(a) The subduction of the Nazca plate beneath the South American continent was verified by the existence of a clearly defined Wadati-Benioff zone with the fol-

lowing parameters: prevailing dip of 12° - 15° to the northeast in northern Perú up to 6°S , 12° - 16° to the east in northernmost Perú and southern Ecuador between 6°S and 2°S , and about 20° to the east in Ecuador between 0° and 2°S , prevailing thickness of 60-90 km, depth of penetration varying along the Perú-Chile trench between 105 and 225 km.

(b) The existence of an intermediate depth aseismic gap in the Wadati-Benioff zone and its close relation to active andesitic volcanism was confirmed for the region of Ecuador and southern Colombia north of the latitude of 2°S .

(c) For the flatly inclined slab between 14°S and 2.5°S an extended aseismic region was found in the Wadati-Benioff zone. The aseismic region starts prevailingly at the depth of 25-40 km, reaching 140-160 km in northern Perú and 90-105 km in southern Ecuador. The Pliocene and Pleistocene volcanism in northern Perú and southern Ecuador appears to be spatially bound to this aseismic region.

(d) A correlation between the depth range of the Wadati-Benioff zone and the major structural units of the Nazca plate implicates a non-uniform rate of subduction and a possible segmentation of the subduction zone along the Perú-Chile trench due to the hampering effect of the main ocean floor elevations and fracture zones.

(e) Taking into account the age of the Pliocene volcanism in northern Perú, its position in relation to the slab, and the total length of the subduction zone, average mean rate of subduction of 6.3 cm/yr was estimated and the beginning of the present cycle of subduction dated to Upper Miocene.

(f) Several seismically active fracture zones, induced in the continental plate by the process of subduction, were found. The whole system of these fracture zones is described in Hanuš and Vaněk (1987).

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