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On the geometry of the Nazca Plate subducted under Central Chile (32–34.5°S) as inferred from microseismic data

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ABSTRACT

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Results obtained from the distribution of local seismicity recorded with a temporarily expanded network in Central Chile during two months in 1986 are presented. Data from the Bulletin of Regional Seismicity for South America (SISRA), between 1965 and 1981 and for depths over 50 km, are added to extend the spatial covering. All of this information evidences the geometry of the subducted plate in ten E–W-oriented cross-sections, 33 km wide.

The passage from subhorizontal subduction north of 33°S to normal subduction is well established as a continuous transition. The geometry of the subducted lithosphere beneath the Chilean territory remains unchanged throughout with a dip of 25°. A difference between segments may be seen to the east of the high Andes: an almost horizontal seismic zone, 300 km wide in the northern part, narrows gradually as we move south and disappears completely near 33°S. This correlates very well with the beginning of active volcanism. It is shown that the vanishing of the horizontal part of the subducted lithosphere represents the transition from subhorizontal to normal subduction. No clear activity is observed deeper than 150 km.

Introduction

Chile is located on the Andean margin, which is characterized by the subduction of the Nazca Plate under South America. As stated by Isacks et al. (1968), the seismicity under the continent presents a well-defined distribution, the Wadati–Benioff zone (W–B), that outlines the geometry of the subducted lithosphere. Several authors (Kausel and Lomnitz, 1968; Stauder, 1975; Barazangi and Isacks, 1976, 1979; Jordan et al., 1983) have observed that different dips are present along the Nazca–South American subduction. These changes in dip added to the maximum observed length of great earthquakes (from the aftershock distribution) led some to speak of a segmentation in the subduction (Swift and Carr, 1974). The space resolution available in early works was not very high because, in the first place, seismologists dealt with very extended regions and, moreover, the quality of the worldwide seismic network was insufficient. Vertical sections that showed differences in the geometry of the subduction were several hundred kilometers wide, putting in evidence only general trends. This was equivalent to spatial averaging over such widths, so that smaller variations were lost. The problem of space resolution and the notion of segmentation was in some way misleading because it implicitly implied the idea of a tear in the subducted lithosphere. Lately, precision has been

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gained with the help of local microseismic networks, and the geometry of the transition between subduction regions with different dip is becoming better known. For instance, Grange et al. (1984) showed that the passage between the two adjacent zones with different subduction in Southern Peru presented a continuous character that had not been pointed out in previous studies with teleseismic data.

Subduction at angles of 25–30° is called "subduction of the normal type", meaning a subduction of the Chilean type as defined by Uyeda and Kanamori (1979). On the other hand, "subhorizontal subduction" makes reference to a gentle dip angle of 15° or less.

Subhorizontal subduction occurs in central Peru and central Chile and it is correlated to characteristic phenomena at the surface. First, no Quaternary volcanic activity is present over these gentle angle subduction zones, thus defining two important gaps in the actual Andean volcanic arc. Second, there is a narrowing of the Altiplano in central Peru and an absence of a central valley in central Chile. On the other hand, subduction is observed to be normal, having a dip angle of 25–30° in southern Peru, northern Chile and south of 33°S. The structure around the Andean Cordillera presents central valleys limited by coastal ranges to the west. Continuous active Quaternary volcanic arcs are present along these segments. Both types of subduction considered here generate a compresive stress regime. Nevertheless, subhorizontal subduction is associated with a stronger coupling of the converging system, in the sense that cumulated stress is not only relaxed through seismic slip but also through continuous deformation. This is thought to be one of the reasons why a stronger and more extended continental deformation is observed over the gently dipping zones. Another feature that certainly plays a role in the generation of the segmentation is the oblique subduction of aseismic ridges offshore (Nur and Ben Avraham, 1981), which intersect the trench near the ends of the low-angle W–B zones (Fig. 1). For example, the dip of the subducted slab under the continent is observed to change abruptly (Barazangi and Isacks, 1976) at about 33°S (Fig. 1). A well-defined subhorizontal subduction is observed to the north, while normal subduction is present to the south. The Juan Fernandez Ridge is found offshore at this latitude and may be the cause of the change in dip (Nur and Ben-Avraham, 1981).

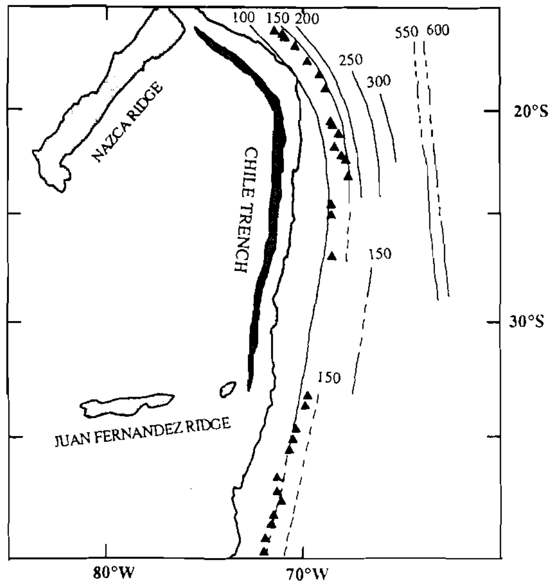

Fig. 1. Map showing ridges, trench, volcanic arc and contours of hypocentral depth. Modified from Barazangi et al. (1976).

The change from subhorizontal to normal subduction, in central Chile, has not been studied in detail with a local network, and only general trends north and south of it have been established from the available teleseismic data. A tear of the subducted lithosphere was inferred on the basis of four cross-sections and the slip vectors of some focal mechanisms in a previous study carried out by Acevedo (1985). Barazangi and Isacks (1976) also inferred a discontinuity based mainly on the general trends of the focal-depth contours of teleseismic data. On the contrary, more precise microseismic studies carried out in Peru evidenced the continuity of the subducted lithosphere (Grange et al., 1984). This result convinced seismologists that lateral interpolation of focal-depth contours was possible. Hereafter, smoothing or analytical surface fitting to hypocenter data distribution, asuming continuity, has been done elsewhere (Bevis and Isacks, 1986).

The purpose of this paper is to contribute to the precise definition of the transition region near 33°S, by the analysis of the data collected during the 1986 survey of microseismicity conducted by a French–Chilean team with a dense array of portable autonomous instruments complementing the permanent Chilean network.

Morphology

The major physiographic features of Chile may be resumed into four units from west to east: the Coastal Range, a central Depression or Central Valley, the Andean Cordillera, and the active volcanic arc within the latter (Fig. 2) (Kausel and Lomnitz, 1968). These major features define a structure of a central valley between the Coastal Range and the Andean Cordillera with the presence of active volcanism from 18 to 27°S and from 33 to 43°S. A structure formed by transverse ranges joining the Coastal Range and the Andes, fills the area corresponding to the Central Depression between 27 and 33°S. A complete absence of active volcanism is observed in the same region (Fig. 2). This difference must be related in some way to the two types of subduction found north and south of 33°S, as stated above.

A clear change in tectonics is observed in the region under study (32–34.5°S), which corresponds to the transition between the two types of subduction.

We see a very strong and extended deformation in the northern part. Going from west to east, we evidence first a region with average topography higher than 800 m, where apparent NNW and ENE conjugate faulting suggests a compressive regime. Further east, the high mountains of the Andean Cordillera are dominated by reverse faulting. Still further to the east, in Argentina, we find the Sierras Pampeanas which are roughly N–S-oriented ranges that commonly reach an elevation from 2000 m to 4000 m. The Sierras Pampeanas are uplifted blocks limited by reverse faulting that place Precambrian and Paleozoic rocks over Cenozoic strata (Jordan et al., 1983). Thus, deformation extends from the trench over more than 600 km to the east.

In the southern part, the Central Valley is well developed and bounded by normal faults, deformation is spread over a narrower zone and mainly concentrated in the Andean Cordillera. A calc-alkaline active vocanic arc is present throughout.

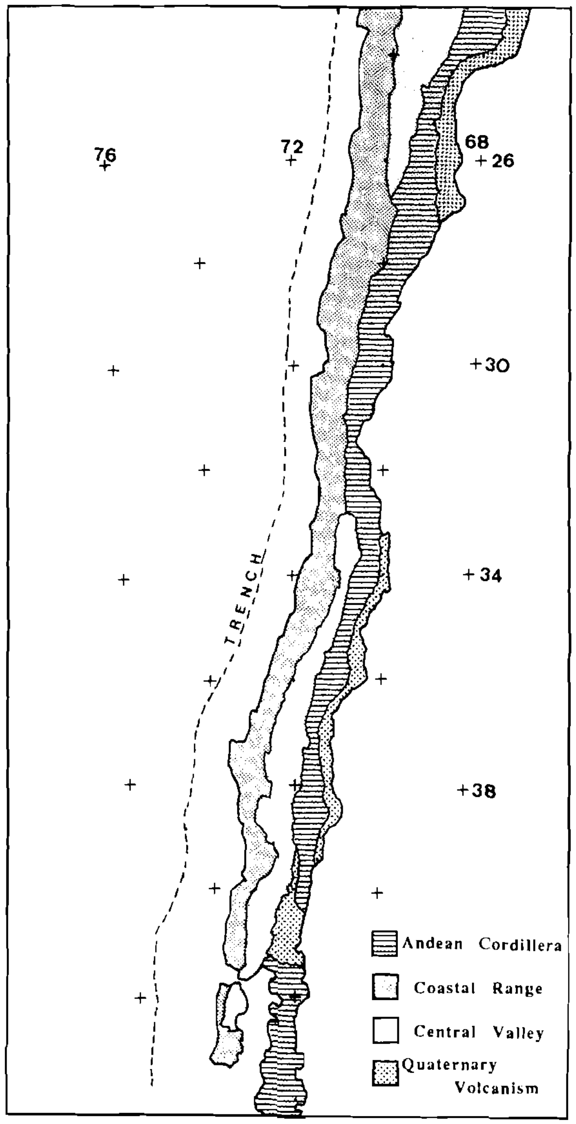

Fig. 2. Principal physiographic features of Chile. It is seen that while the Coastal Range and the Andean Cordillera present a continuity from north to south, the Central Valley and the Quaternary Volcanic Arc are absent between 27 and 33°S. Modified from Kausel et al. (1968).

The transition in style of deformation observed from north to south for the whole region of study is gradual. This transition is evidenced by the distribution of the branching of ranges from the Andes towards the west, transverse ranges that reach an elevation of more than 1500 m. Branches may be observed near Colina, San Francisco de Mostazal and San Fernando, showing different

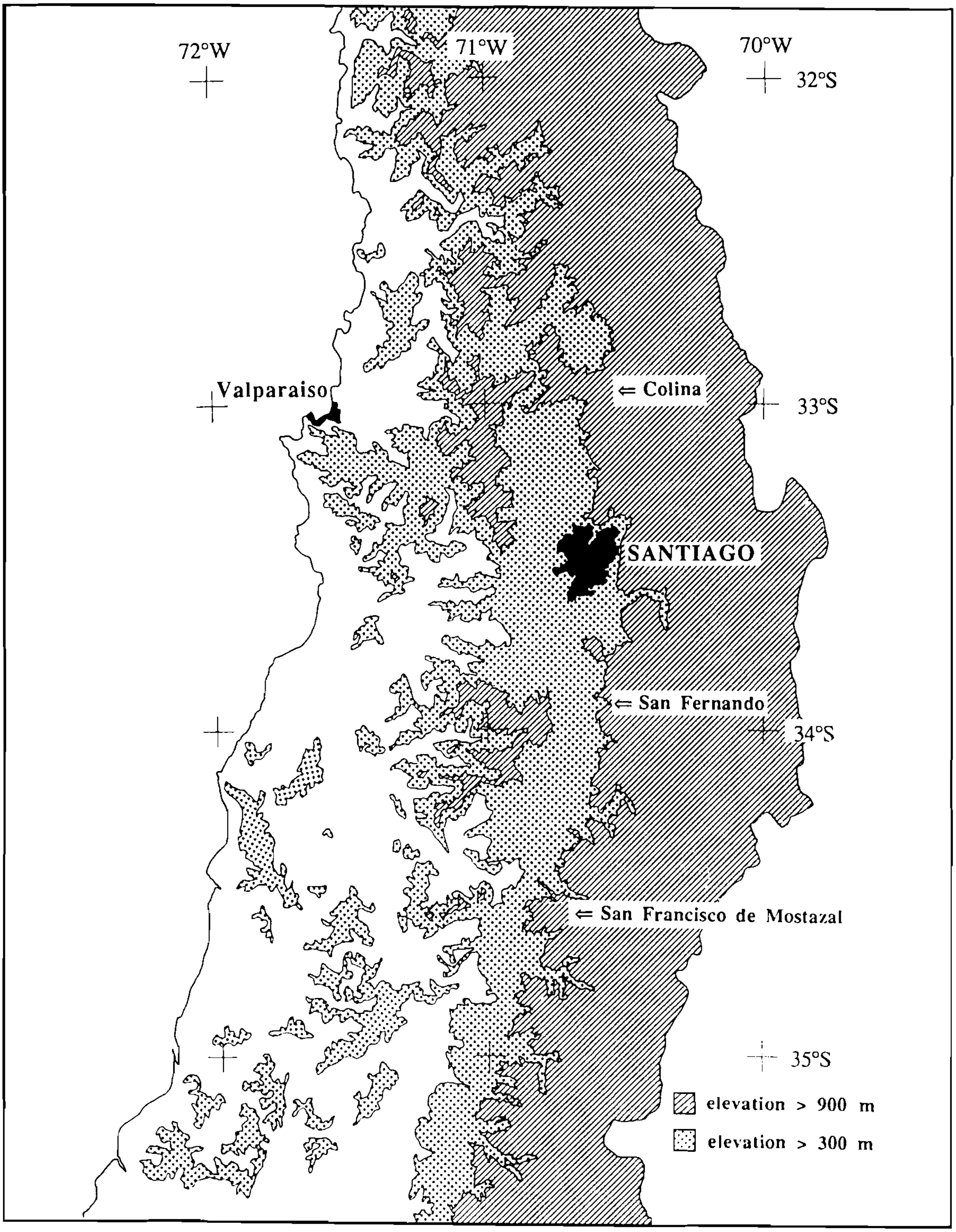

Fig. 3. Topography of the region of study. Arrows indicate the partially developed transverse ranges near Colina, San Fernando and San Francisco de Mostazal.

degrees of importance (Fig. 3). These summits can be considered as incompletely developed ranges filling the central depression. Hence, the transition can be thought of as a gradual superposition of transversal ranges over a central valley.

Data and analysis

The local network of 10 permanent telemetred stations, maintained by the University of Chile, is located in central Chile between 32 and 34°S. The permanent network was expanded and completed for the present study with 10 portable smoked-paper-recording Spregnether MEQ-800 stations and 4 digital recording GEOSTRAS stations (Fig. 4). The MEQ-800 stations worked with L4C vertical seismometers with a natural frequency of 1 Hz and the GEOSTRAS with 3-component L4 seismometers. Smoked-paper stations were visited every two days in order to change the paper and to tune WWV radio time signals in order to control the drift of the internal clock. The GEOSTRAS stations were visited every four days and they received OMEGA time signals continuously.

The determination of the hypocenters was performed with the programs HYPO71 (Lee and Lahr, 1978) and HYPOINVERSE (Klein, 1978) and using a velocity structure model of flat homogeneous layers determined by Acevedo and Pardo (1984). A first location was made with HYPO71 in order to have an estimation of the depths and to check out wrong phase readings. Events were grouped by depth in lots of 10 km. After reading the doubtful time phases again, a final location was performed with HYPOINVERSE. In a subduction region such as the chilean one, the crustal velocity structure presents an east–west heterogeneity (Acevedo and Pardo, 1984). In order to eliminate, or reduce, the bias of using a flat

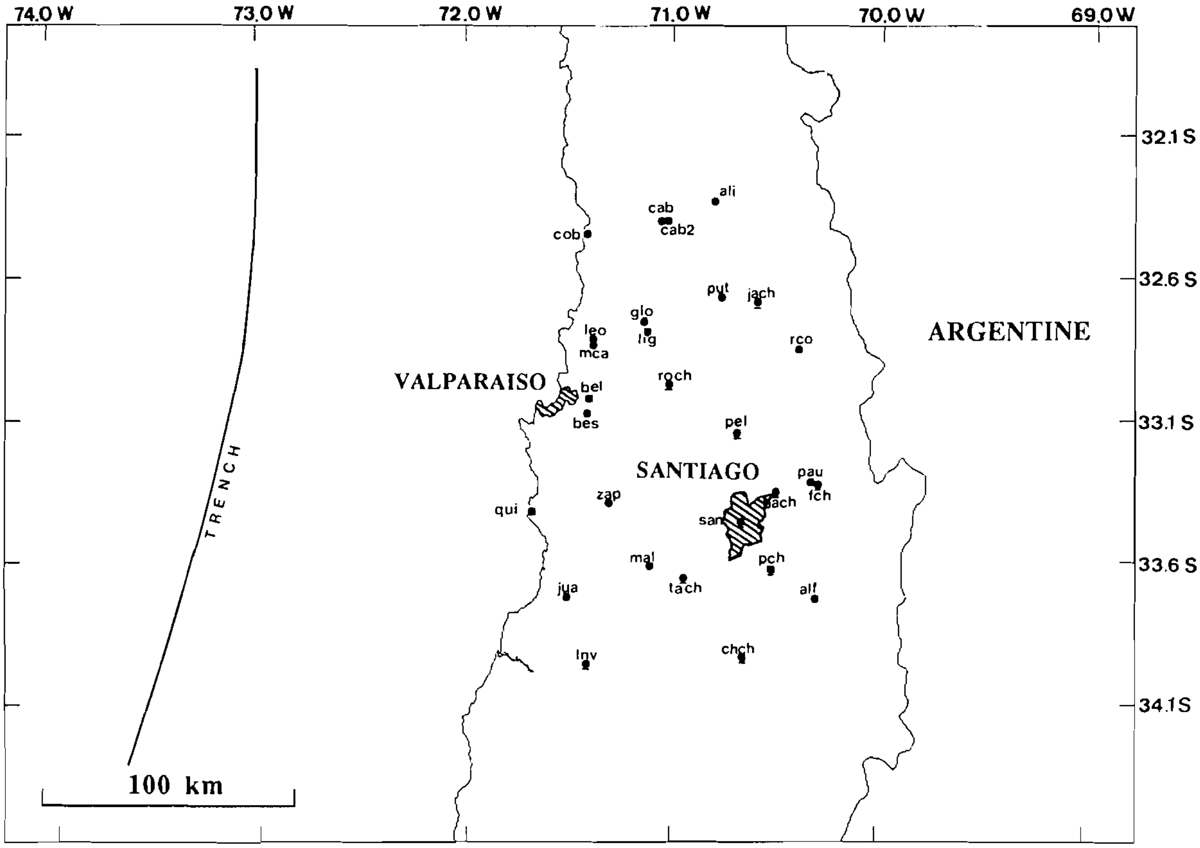

Fig. 4. The two month expanded local network. Simple symbols indicate portable stations and underlined symbols permanent network. The network occupies a region of 150 × 170 km^2.

layered structure in a region of crustal thickening, a delay model for each station was used (Comte et al., 1986). Depending on whether the event was offshore, inland or in the cordillera, a different delay model was taken. We also corrected the travel times by the elevation of the station.

The criteria for selecting the data were: an RMS < 0.4 s and time residuals not larger than 0.4 s in P-phase readings, and 1.0 s in S-phase readings that were effectively used in the determinations. The uncertainties in P- and S-phase readings are estimated to be not over 0.2 and 1.0 s, respectively, and to be the combined result of reading errors and clock drift. All events detected by the permanent network were read in order to have the largest number of phase values for each location. No geographic criteria were imposed in selecting the events, and all of those which satisfied the previous RMS and residual criteria were retained. All events have at least two S-phase readings with non-zero weight in the final location. The total number of hypocenters obtained with these criteria was 356, over a period of two months, with computed errors in epicenter of 2.5 km and depth of lower than 5 km.

Results

In Figure 5 we present the distribution of the epicenters localized with the expanded network. The distribution shows some clustering of events in the coastal region. These are aftershocks of the March 3, 1985, Valparaiso earthquake. Also two crustal clusters are observed (Fig. 6B), one near Santiago (33.4°S) and the other to the southeast of Rancagua (34.3°S) in the Cordillera. Finally, it can be seen that, in the northern part, the distribution of seismicity spreads slightly to the east.

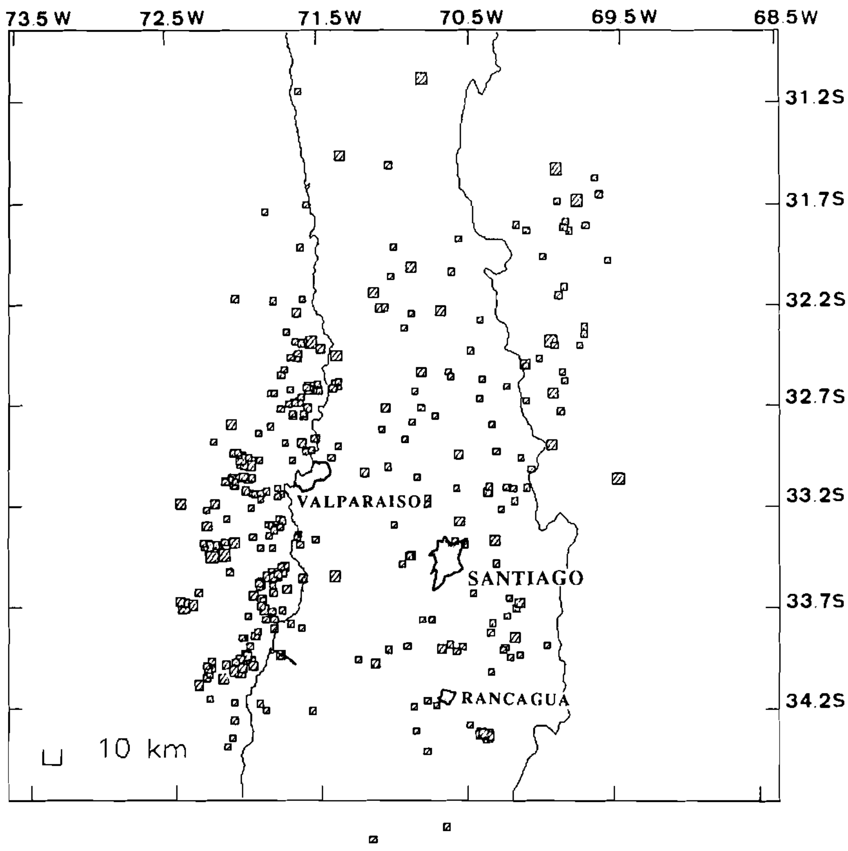

Fig. 5. Map of all earthquakes located with the expanded network during the two months of the investigation. The located events were those recorded by the temporary and the permanent network at the same time, since these latter instruments had a lower gain than the temporary ones. Relative size of the symbols is proportional to magnitude.

Cross-sections, north and south of 33°S, show that the seismicity clearly defines the slab subducting under Chile at an angle of about 25° all along the zone, down to a depth of about 110 km (Fig. 6A,B).

The well-localized seismicity distribution did not clearly evidence the change in slope of the subducted slab, which is more to the east, due to the extension of our expanded network. To compensate for this drawback we added the data from the Catalogue of Earthquakes for South America (SISRA, 1985a, b). In this way we extended our set of data farther to the east, taking care that only good-quality hypocenters were added.

Good epicentral locations, though not as precise as those obtained from a dense local network, are available since the WWSSN station network has been in operation (1965 approximately). We considered that all the events in the SISRA catalogue, between 1965 and 1981, and with more than 15 time phases weighted in the determination of the hypocenter, had a good depth control. We may observe that adding SISRA data does not greatly change or increase the dispersion around the geometry of the slab in the western part (Fig. 6). Depths are well controlled to the east, because pP-phases are well developed for hypocenters of the order of 100 km. These two arguments permit us to say that

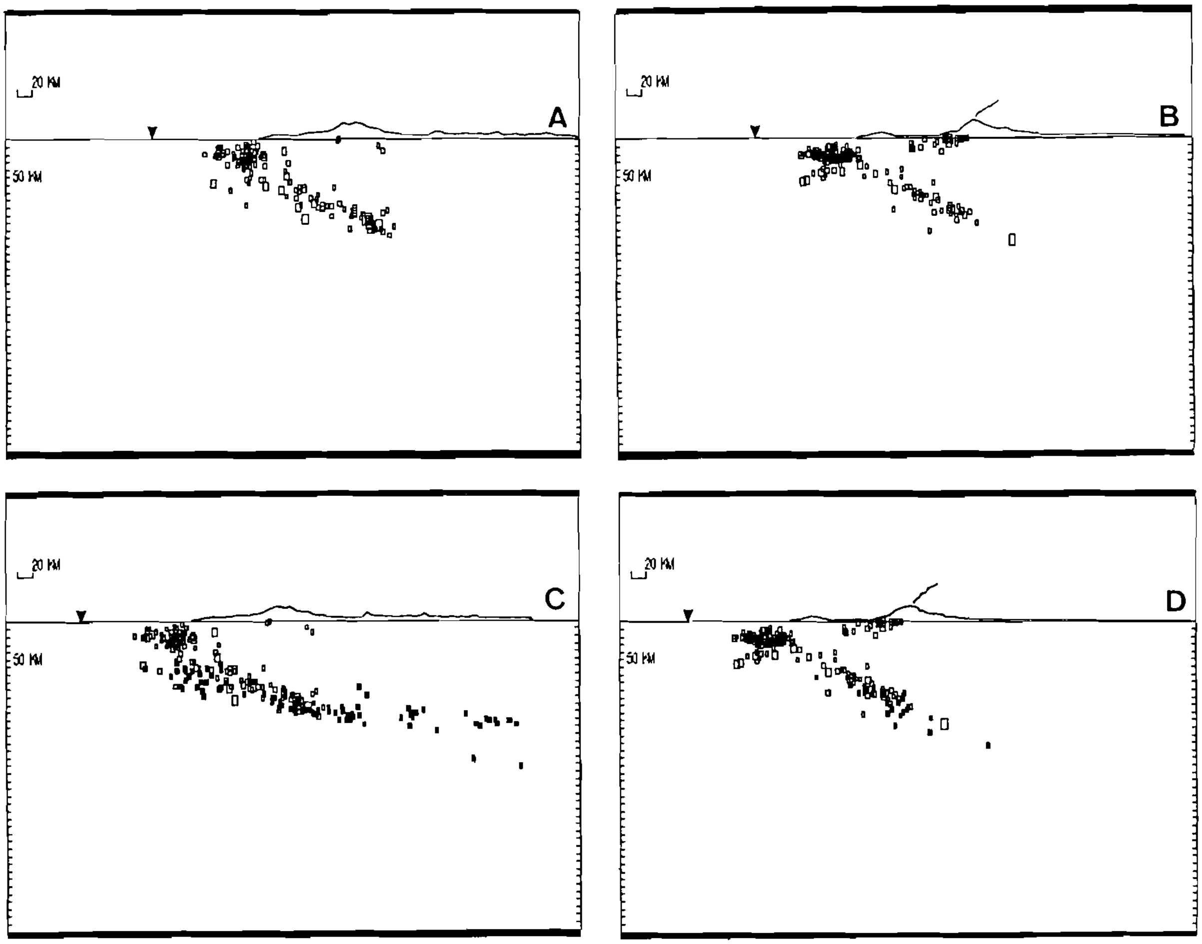

Fig. 6. Cross sections of seismicity: (A) events north of 33°S located with local network; (B) events south of 33°S located with local network; (C) events north of 33°S including the SISRA catalogue 65–81 showing the extention of the subducted slab to the east; (D) events south of 33°S including the SISRA catalogue 65–81. Events located with the local network are in open symbols while SISRA events are in filled symbols. Inverted triangles indicate the location of the trench axe. Generalized topography is exaggerated.

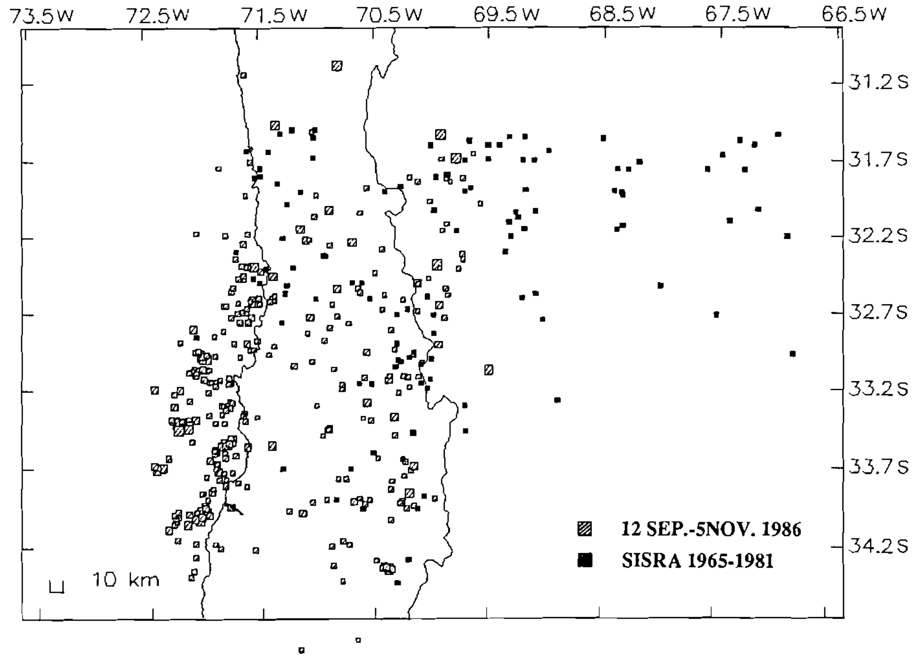

Fig. 7. Map of all earthquakes used in the study. Hatched squares are events located with local network and filled squares are events from the SISRA catalogue. In the northern half we observe the extension of the activity to the east, contrasting with absolute quiescence to the south.

the two set of data combine in a relatively homogeneous way. Thus, 236 events were selected between 1965 and 1981 from the SISRA catalogue, making a total number of 592 earthquakes to be used in the present study.

Combining the data from the local expanded network and the selected data of the SISRA catalogue, we find that the epicenter distribution expands much more to the east but only in the northern part (Figs. 6C,D and 7). In the cross-sections we identify, to the west, a cluster of aftershocks of the 1971 La Ligua earthquake (Fig. 6C) and a cluster of the 1985 Valparaiso earthquake (Fig. 6D). With this population of hypocenters, we constructed ten cross-sections oriented E–W with a half width of 16 km and taken every 33 km (Fig. 8). Cross-sections normal to the trench did not to present any difference, appearing to be insensitive to orientation. In the different sections constructed to infer the geometry (Fig. 9), we observe that for the first 100 km in depth the W–B zone dips with an angle of about 25°. This angle does not change substantially from north to south, showing that under Chile there is no significant change in the dip of the subducted slab. Such a change is only observed farther east, beneath Argentina.

The earthquakes that determine the change in dip are those from the SISRA catalogue which,

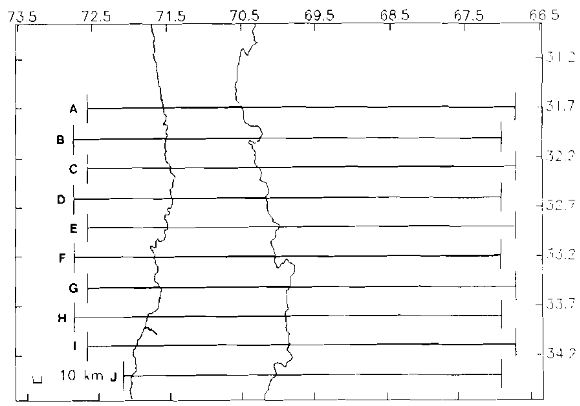

Fig. 8. Location of cross-sections made to observe the geometry in depth. All sections have a half-width of 16 km and are situated at intervals of 33 km.

as stated, have a good depth control because pP-phases are well developed at these depths. Thus, the data from the local network controls the geometry of the subduction for the first 250 km from the trench and the SISRA catalogue data the geometry to the east of these 250 km.

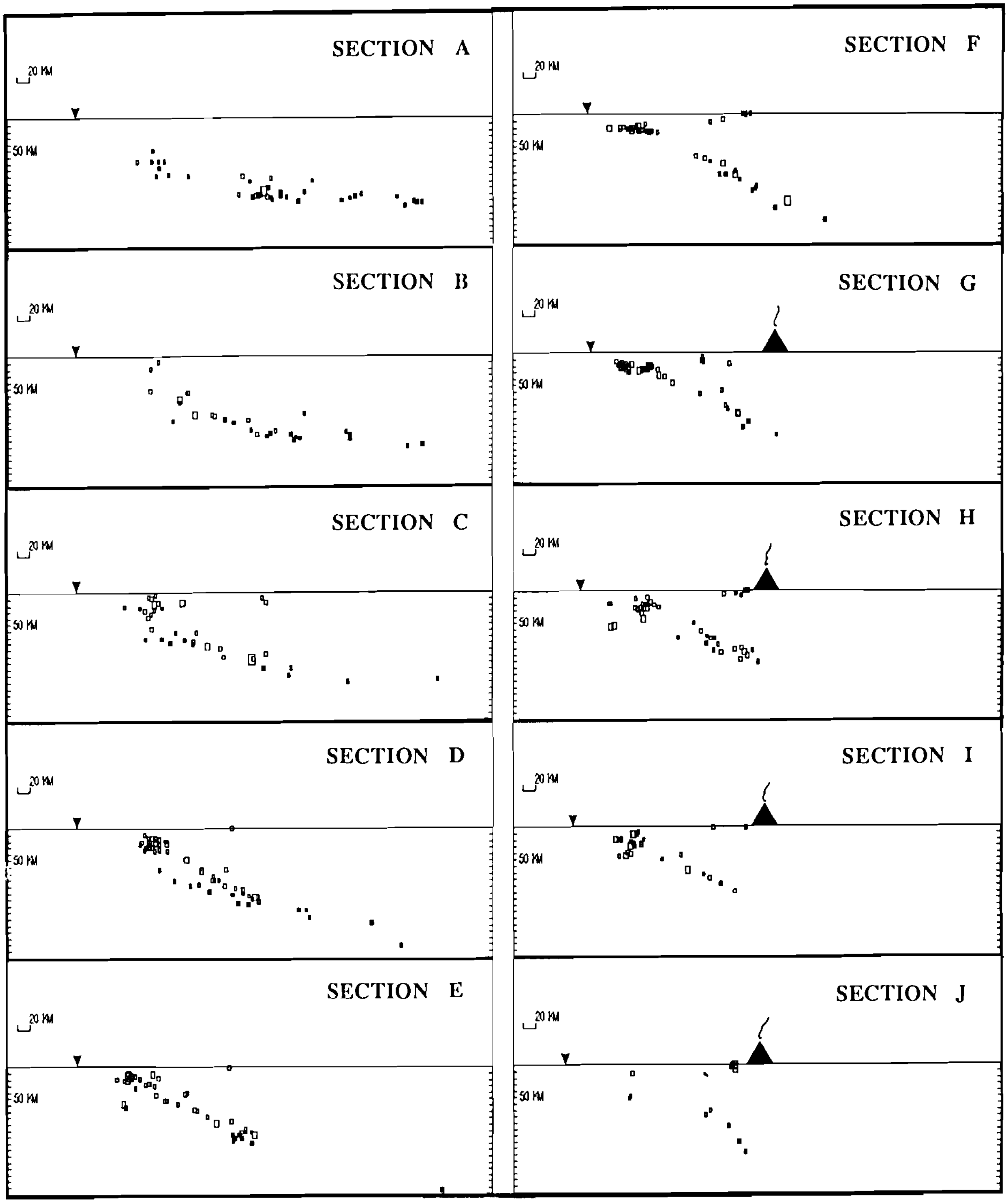

Fig. 9. Cross-sections of seismicity made at 33-km intervals from north to south with a width of 32 km. It can be observed that the variation in the geometry of the subducting slab is more like a shortening of the flat part, leaving the part towards the trench with no significant change. Inverted triangles show the location of the trench axe and larger upright triangles show the volcanic arc.

As mentioned above, it can be observed that the dip is approximately constant (25°) between 73 and 70°W. But the subducted slab presents a subhorizontal portion, from 70°W to the east, that shortens as we go south disappearing completely from Santiago to the south.

It is important to remark that, except for two events, the maximum depth reached by the seismicity in all sections is 150 km. No significant activity was observed below this depth. This contrasts with the observations made in southern Peru (Grange et al., 1984).

It can be seen that the seismicity defines an inclined region of about 20–30 km of thickness in each section, which is probably thinner taking in account dispersion errors. It is seen that surface volcanism appears approximately where the activity reaches the depth of 150 km, if there exists a wedge of asthenosphere.

The ten sections define the geometry of the subduction in a very precise way. The transition between the horizontal and normal subduction presents itself as a continuous spatial shortening of the horizontal clustering of earthquakes, and not as a discontinuous rupture.

Conclusions

The main result of this study is a precise determination of the geometry of the subducted lithosphere and a description of how it changes from north to south. We have seen how this transition can influence the continental morphology of our zone of study, and how the tectonics is explained by the convergence of the two types of subduction. This results contrasts with the transition found in south Peru by Grange et al. (1984). They find a slab which changes gradually in dip from one zone to the other, while we find a horizontal part that shortens until it disappears. They find activity up to a depth of 250 km while ours is confined to the upper 150 km. The interpretation of the absence of activity below 150 km presents an interesting geodynamic problem. It could be attributed either to the presence of a shorter (younger) slab or to an aseismic subduction due to rheology. In fact, aseismic subduction under 150 km has been interpreted as a the result of partial melting of the subducted slab (Hanus and Vanek, 1984).

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