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A Double-Layered Seismic Zone in Arica, Northern Chile

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Abstract A double layered seismic zone is determined in Arica, northern Chile using locally recorded events. At depths >100 km two planes of seismicity can be observed: one dipping at ~30°E with ~10 km of thickness and a second parallel plane 20-25 km deeper, with the same average thickness. Fault plane solutions for both layers show a wide variability, even between nearby events. The genesis of the Arica double seismic zone seems to be independent of the age, the relative convergence rate and direction of the Nazca plate, because all of these parameters are almost the same along the whole northern Chile and a clear separation of the seismicity into two layers is only observed around the Arica elbow. Moreover, it cannot be responsible of the double layered seismic zone because no similar significant changes are observed in the other well studied double seismic zones.

Introduction

A global view shows that seismicity along subduction zones usually delineates a single well-defined surface, with earthquakes distributed in depth from the surface down to several hundred kilometres. Between the trench and a depth of 20 km, the seismicity is weak or absent, between 20 to 55 km most of the earthquakes are localised along the interplate contact [Ruff, 1996]. Below this depth, the seismicity presumably occurs within the subducting lithosphere, with a clear minimum at a depth of about 350 km [Gutenberg and Richter, 1952; Kirby et al., 1996]. Between the coupled zone and 350 km depth, downdip tension is the dominant character observed with teleseismically and also locally recorded events [Isacks and Molnar, 1971; Ruff, 1996; Delouis et al., 1996].

Since about two decades the existence of double seismic zones (DSZ) along localised segments of some subduction zones has been recognised. However only few of them have been studied in detail: beneath Honshu [Hasegawa et al., 1978 ; Kawakatsu, 1986], beneath Central and East Aleutians [Engdahl and Scholz, 1977; Abers, 1992, 1996] and beneath the Kuril-Kamchatka arc [Gorvatov et al., 1994; Kao and Chen, 1994; 1995]. They are characterised by a double-planed distribution of intermediate depth earthquakes, vertically separated by 20 to 40 km, at depths between 70 and 150 km. The upper plane seems to be just below the top surfaces of the subducting slab, and the lower plane is consequently within the subducted mantle [Abers, 1996]. From the first studies in northern Honshu, it was determined and further largely accepted that the state of stresses in the two planes was opposite. If the dip angle is not large enough (<45°), the upper plane is characterised by reverse faulting and down-dip compression, while the lower one was characterised by normal faulting and down-dip extension [Kao and Chen, 1994]. However, a precise survey in the Aleutian DSZ has shown that, at least there, even if down-dip extension is dominant in both planes, any type of faulting is present [Abers, 1992].

With the development of high quality global networks and the consequent improvements of waveform modelling, several DSZ have been identified during the past years. Most of them are defined by very few events spanning along hundreds of kilometres along the strike of the trench, and it is therefore almost impossible to asses the continuity or the segmentation of the phenomena. On the other hand, even if an unusual focal mechanism has been determined at intermediate depth in a subduction zone, it is also important to separate the double-layered seismic zones independently from stress-segmented criteria [Fujita and Kanamori, 1981].

After the first DSZ has been identified, the subduction of the Nazca plate underneath South America has been studied to look for the presence of such a DSZ. The difficulties associated to the use of teleseismically recorded events are illustrated in the works of Barazangi and Isacks [1979], Kono et al. [1985] and Cahill and Isacks [1986]. Using locally recorded microearthquakes, Comte and Suárez [1994] showed evidence for a DSZ in northern Chile, south of this study, based on focal mechanisms, a result that should be confirmed by a real separation of the seismicity into two planes.

In this work we present the results obtained using locally recorded microearthquakes in the northern edge of the northern Chile seismic gap, along the Arica elbow (Figure 1).

Data and Methods

The data used consisted of two sets: (1) from a telemetric short-period seismic network of 9 stations that has been operating since December 1994 as a joint research project among the University of Chile, the University of Tarapacá, the Institut de Physique du Globe de Strasbourg, France and the Institut de Recherche pour le Développement, France and (2) from a dense temporary short-period seismic network of 18 vertical and 10 three components digital stations, joint by 6 vertical analog stations (Figure 1), deployed from the coastline to the Altiplano from June to August, 1996. The second dataset contains about 1000 microseismic events while the first has about 3900 events.

The set of body-wave arrival times of microearthquakes recorded was used for preliminary hypocentral determination using a modified version of the HYPOINVERSE program [Klein, 1978]. The crustal P-wave velocity model was the same flat layered model used by Delouis et al. [1996]. Each event is located with different trial depths (between 0 and 250 km, with an increment of 10 km), in order to minimise the effect of dependence of the final hypocentral determination with the initial trial solution.

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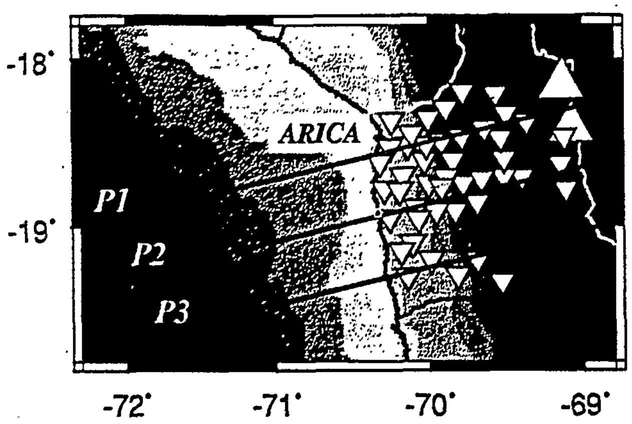

Figure 1 Spatial distribution of the permanent telemetric and the temporary networks of Arica (white inverted triangles). Three profiles along the direction of convergence are also shown. The Parinacota and Guallatire volcanoes with recent activity are represented by white triangles.

From the initial dataset, a subset of the best constrained hypocenters was selected to be used in a joint inversion for hypocentral locations and 3D body-wave velocity structure [Comte et al., 1997]. The inversion approach is analogous to that used elsewhere [e.g., Abers, 1990; Abers and Roecker, 1991; Comte et al., 1994]. The area of study is parameterized as a set of constant velocity blocks, body wave velocities are determined as independent parameters within each block, using linear velocity gradients for ray tracing. Following the inversion, 4480 earthquakes were relocated with the 3D model. Stable and well-constrained locations were found for 3083 events, using criteria of convergence and condition number of hypocentral inversion similar to Abers and Roecker [1991].

The analysis of the variation of the hypocentral locations when 1D or 3D velocity models are used shows that, within the coverage of the network the epicentral differences are negligible, reaching maximum values less than 2-3 km. The average variations in depth vary less than 5 km. The results of this analysis show the robustness of the location of the selected events.

The improved ray geometry makes possible to determine single-event focal mechanisms using individual first motion polarity for some reliable events along the subducting plate. The polarity of each station was tested in laboratory and by comparing observed with expected first motion for teleseismic events.

Results

Three cross sections along the average direction of the convergence of the Nazca plate beneath South America (N77°E) are shown in Figure 2; the half-width of the P1 to P3 profiles is 20 km. Some selected focal mechanisms are presented on Figure 3 (corresponding to the P2 profile, but with a half-width of 40 km) in a vertical back hemispheric projection along the convergence direction of the Nazca plate.

Seismicity at Depths Lower Than 100 km This seismicity can be separated in three groups (Figure 3): that occurring along the interplate contact, that located above it, and the shallow one observed beneath the Altiplano. The interplate contact is defined by fewer events compared with that observed to the south, in Iquique [Comte and Suárez, 1995] and in Antofagasta [Delouis et al., 1996], using local seismic data. It is possible to define an average dip angle of ~20° between 25 and 50 km in depth. Considering the lack of coverage oceanward of the seismic network, the majority of the focal mechanisms are not well constrained along the coupled region between the trench and the coast. An unusual high level of seismicity can also be observed above the interplate contact. Their focal mechanisms suggest that normal fault events are located at shallower depths than the reverse ones (Figure 3). The shallow seismicity located beneath the Altiplano could be correlated with the active volcanoes (or more likely the active faults) in this region.

Seismicity at Depths Between 100 and 150 km Most earthquakes below 100 km depth lie in a single zone, about 10 km thick, that is almost planar down a depth of 150 km, dipping ~30° to the east. A second parallel planar zone 20-25 km beneath (perpendicular distance between both layers) is observed with fewer events and an average thickness of ~10 km (Figures 2 and 3). Fault plane solutions for these intermediate depth events vary significantly, even between nearby events, (for example events 9 and 10 in the shallowest layer, and events 20 and 21 in the deepest layer). Moreover, focal mechanisms of events located at approximately the same depth and the same distance from the trench can present opposite polarities observed in almost all the stations (for example events 12 and 14 in the shallowest layer, and events 21 and 22 in the deepest layer).

Discussion

The first attempts to define a double seismic zone in northern Chile were done using teleseismically recorded earthquakes [e.g., Kono et al., 1985; Cahill and Isacks, 1986]. After some controversial interpretations it was just possible to conclude that there is no clear evidence for a double-planed seismic zone in

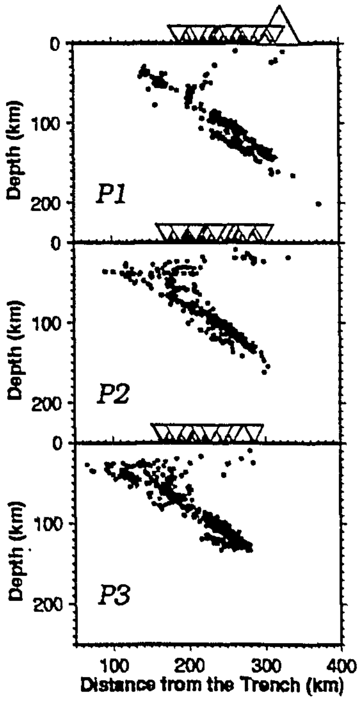

Figure 2 Cross-section of the reliable hypocenters (circles) determined with the 3D velocity model, along the three P1, P2, and P3 profiles shown on Figure 1. Projections of the seismic stations (inverted triangles) and active volcanoes (triangles) are also presented.

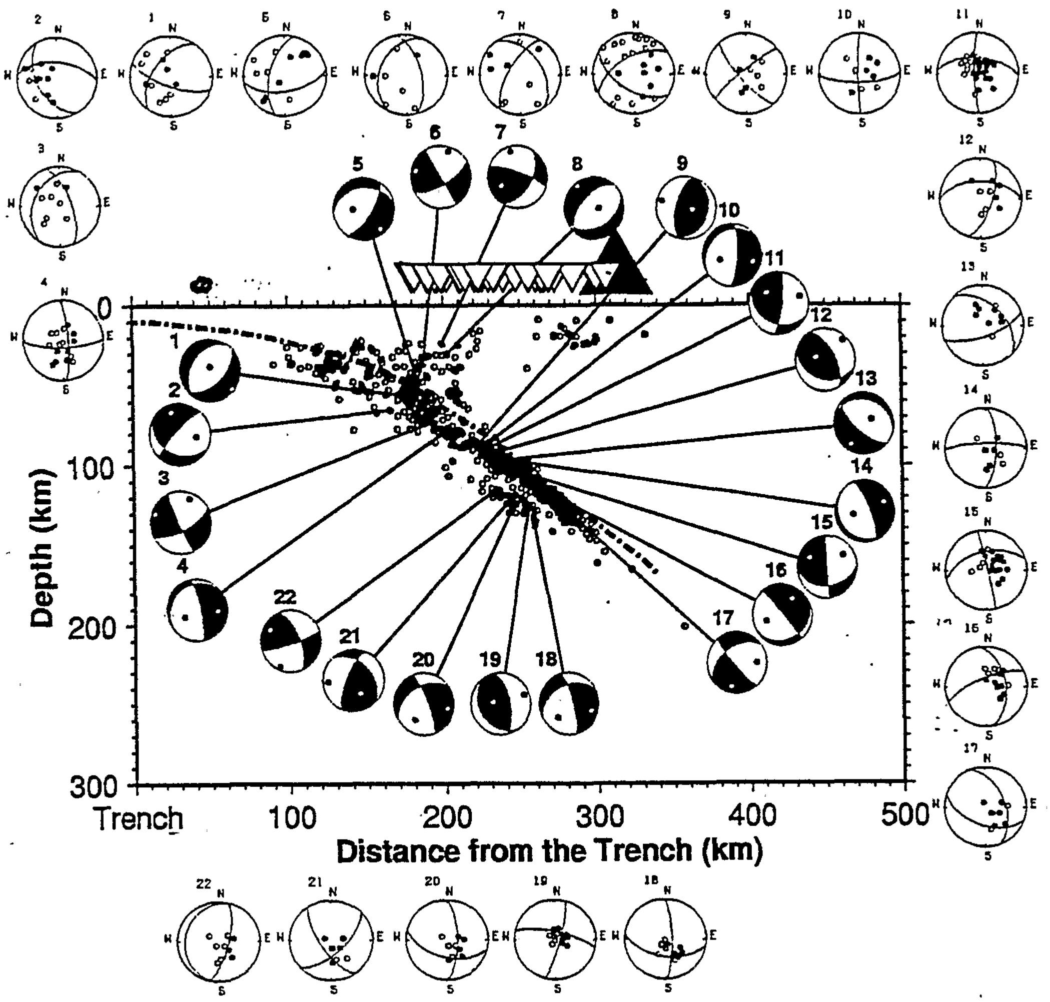

Figure 3 Cross-section of the reliable 3D hypocenters determined (open circles) along the ±40 km wide P2 profile shown on Figure 1. Some focal mechanism solutions projected on the vertical lower hemisphere are also shown. The segmented curve represents the hypothetical upper part of the subducting Nazca plate in the region. The lower hemispheric projection of each focal mechanisms, with the first motion polarities is also shown. Projections of the seismic stations (inverted triangles) and active volcanoes (shaded triangles) are also presented.

this region. However, it exists at least one compressional event (1977) with a focal depth located beneath the tensional ones [Comte and Suárez, 1995]. Therefore, using only teleseismically recorded events, it is very difficult to establish the existence of double layered seismic zone with the currently location routines, however it is no so, if the source parameters are carefully determined [Kao and Chen, 1994, 1995].

The DSZ previously observed with microearthquake surveys in northern Chile may be interpreted as zones that present a combination of tensional and compressional faults in a close spatial relationship, that can be observed mainly using locally recorded events [Comte and Suárez, 1994]. This work presents reliable data that show a double layered seismic zone in Arica, northern Chile located at depths between about 100 to 150 km, with compressional and tensional events at almost the same depth (Figure 3).

The Arica DSZ can be observed mainly with microseismicity, therefore it is a phenomena that depends on the magnitude threshold used. In the same way, the extreme variability of the focal mechanisms observed in both planes, do not necessarily represent the overall stress/strain regime at the depth where the DSZ is observed. However, there are some things that can be established: considering that the Arica DSZ is a localised phenomena in the northern Chile region, it seems to be independent of the age (84 My), the relative convergence rate (~8.3 cm/yr) and convergence direction (N77°E) of the subducting slab, because all of these parameters are almost the same along the whole northern Chile region [Pitman et al., 1968 ; Chase, 1978 ; Minster and Jordan, 1978 ; DeMets et al., 1990]. Moreover, the Arica elbow can not be responsible of the Arica DSZ, because no similar changes along the strike of the trench are observed in other well studied double seismic zones. In fact, it can be noted that the general patterns of the Arica DSZ, like the maximum depth and the spatial separation of the two seismic bands are very similar with that observed in the Alaska Peninsula where no elbow is present [Abers, 1992, 1996].

Kao and Liu [1995] presented a possible interpretation for the seismogenesis of DSZ based on their studies along the Kuril-Kamchatka and Japan subduction zones. Even that the general pattern of the stress distribution at intermediate depths is not so similar with that observed in the Arica DSZ, their hypothesis that microearthquakes in the upper portion of the top layer can be probably caused by conventional mechanisms such as dehydration of subducted materials and facies change from basalt to eclogite, whereas the lower layer could be associated with metastable phase transition, can not be rejected by our results. In the same way, the presence of melt-rich regions formed near of the mid-ocean ridges at the base of a thermal boundary layer, that occasionally crystallised into the plate without ascending to the surface proposed by Abers [1996] is still a viable alternative to explain the lower-zone seismicity.

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