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Flat subduction beneath the Andean region from seismological evidences

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Introduction

The aim of this paper is to present the current knowledge on seismotectonic characteristics in the Andean region, with the purpose of discussing the tectonic processes that control the occurrence of flat portions of the subducted Nazca plate in western South American. Together with the flat portions of subducted slab some other peculiar seismotectonic features are present beneath that region: the absence of seismic activity between 200/300 km and 500 km of depth; the deep South American earthquake focal mechanism, which until now has not been satisfactorily determined; and the occurrence of deep earthquakes, apparently isolated, in extreme north, and eastwards of the southern portion of deep earthquakes.

To find the origin and to explain the existence of flat portions of Wadati-Benioff Zone (WBZ) beneath Andes, we have to consider those peculiar features together, because it seems they are being provoked by the same mechanism. To do this, it is necessary firstly to analyse the shape and spatial distribution of those features using reliable hypocentres of earthquakes occurred in that region. Data to carry on this task were taken from relocations of hypocentres determined by ISC, and NEIC for $m_b \geq 4.0$ earthquakes occurred from 1964 to 1995, performed by Engdahl et al. (1998), and updated later in up to 1999, and selected ISC hypocentral determinations of $m_b \geq 4.0$ events, increasing the catalogue of good quality hypocentres until 2002.

Spatial distribution of Andean earthquakes

All epicentres of the catalogue already mentioned are plotted on the map of Fig.1. The region located between around 3°S and 14°S, occupying the northern and central regions of Peru with around 1,200x450 km^2, comprises an internal portion with a clear low level of seismic activity (see Fig. 1). AA' and BB' sections in Figs. 2a and 2b present the shape of WBZ below that region showing a flat slab in northern and central Peru, respectively, and the lack of seismic activity between 200 and 500 km of depth. Another peculiar feature of this portion of the Andean region with flat slab is the complete absence of active volcanism.

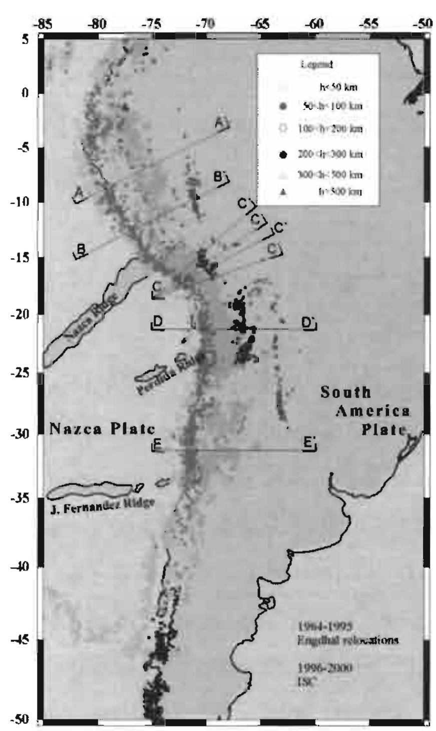

Figure 1. Andean region seismicity showing the main oceanic aseismic ridges

Between 27°S and 33°S, there is a region of around 700x300 km^2, comprising another portion with low level of seismic activity, and outlining another flat segment of WBZ, as seen in EE' section of Fig. 2c. This flat WBZ segment beneath central/northern Chile, which is smaller than the one existent below central and northern Peru regions, does not present too volcanic activity, and finishes at around 200 km of depth.

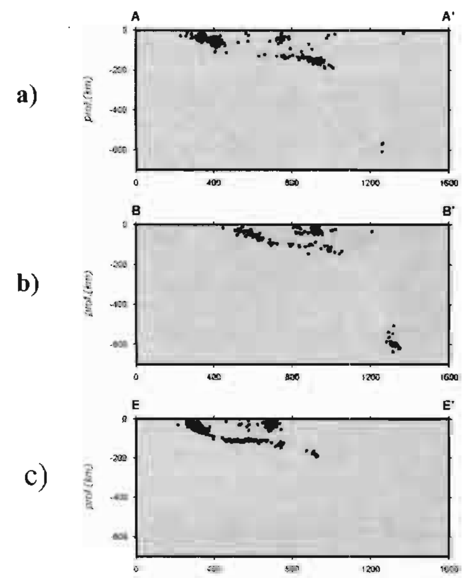

Figure 2. Vertical sections in northern (a) and central (b) Peru, and in central (c) Chile, following the lines shown in Fig 1.

Probable origin of flat portions of subducted Nazca slab

With regards to the origin of flat portions of subducted slab beneath the Andean region, the more admissible hypotheses are those ones that relate the flat portions to low-density aseismic oceanic ridges. Pilger (1981) related the flat slab portions to an extension of Nazca and Juan Fernandez ridges, in Peru and Chile respectively, based on the symmetry models for oceanic floor expansion, as well reconstructions of hot spots inside the plates; Nur & Ben-Avraham (1981) proposed a NW migration of the collision zone between the buoyant ridges with South American plate, without assigning the cause for that migration.

Berrocal & Fernandes (2004) support the second hypothesis, giving, however, an explanation for the cause of the collision zone NW migration based on their hypothesis of "top-to-N-NW shear of subducted Nazca plate". The collision zone migration idea is in agreement with the results presented by Von Huene et al. (1996), who found evidences of 800 km migration of subducted Nazca ridge along Peru-Chile oceanic trench. Their interpretation, see Fig. 3, is the ridge entered Peru-Chile trench about 8 Ma, at 8°S, and migrated southwards to its present position in 15°S. Berrocal & Fernandes' (2004) interpretation of those results is a N-NW migration of the convergence zone, where Nazca ridge subducts at 15°S, given conditions for the formation of the flat slab beneath central and northern regions of Peru. Similar explanation can be given in relation to the flat slab portion beneath central/northern region of Chile and Juan Fernandez sea mountain that subducts with Nazca plate in the extreme south of that flat slab portion. The contour map of Fig. 4, constructed with the relocated hypocentres data, shows clearly the effect of those oceanic ridges in the flat subducted slabs.

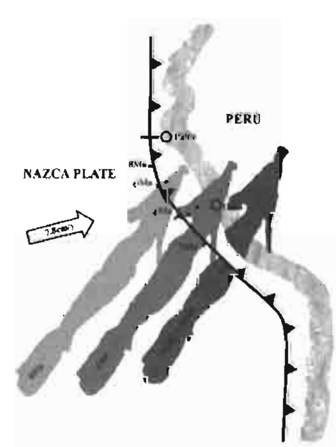

Figure 3. Nazca ridge drift during the last 8 Ma, according to Von Huene et al. (1996).

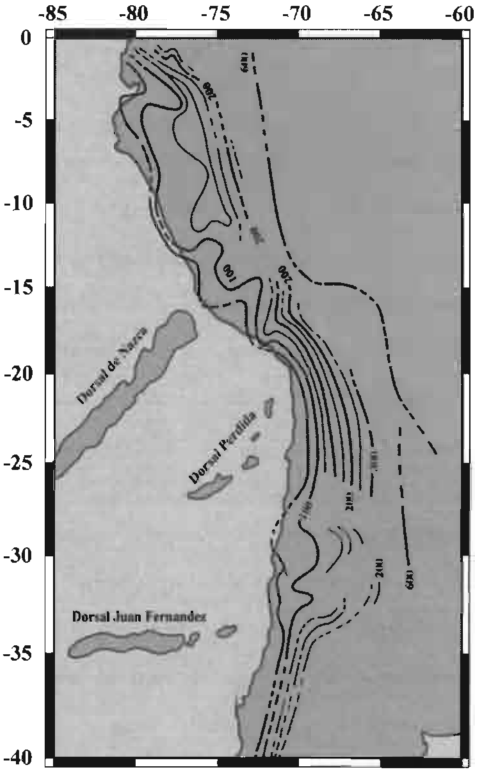

Figure 4. Contour map of the WBZ beneath Andean Region from relocated hypocenters of Engdahl et al. (1998).

The top-to-N-NW shear of subducted Nazca plate hypothesis

Spatial-temporal distribution and other features of WBZ seismic activity beneath the Andean region were used by Berrocal & Fernandes (2003a,b) to propose the "top-to-the-N-NW shear of the subducted Nazca slab" hypothesis, to offer a process for explaining the existence of peculiar and controversial seismotectonic features related to WBZ morphology, and to the origin and mechanism of deep focus earthquakes, besides them the existence of flat portions of subducted Nazca slab.

According to those authors (see Fig. 5), the portion of subducted Nazca plate, which in surface is now between latitudes 23° S and 01° S, is under a shear torsion process in such a way that the extremes of its deepest portion, which includes the deep earthquakes with h>500 km, are presently beneath near 29° S and 06° S, respectively. These latitudes, or probably more to the south, have probably been the original latitudes of the surface portion of Nazca slab in the past, at least 8 Ma ago, just before the beginning of the current shear process. This process, which could be causing a northwards torsional displacement of subducted Nazca plate, may be provoked, according to those authors, by a northwards component of a probable N-NW lateral migration of subducted Nazca plate proposed by Garfunkel et al. (1986), as shown in Fig. 6. The displacement produced during that migration should be larger at the surface portion of the subducted slab.

Possible explanation for other controversial seismotectonic features in the Andean region

The absence of seismic activity below 200/300 of depth in subducted Nazca slab could be attributed to large temperatures and pressure existent in the upper mantle at those depths, which do not permit the

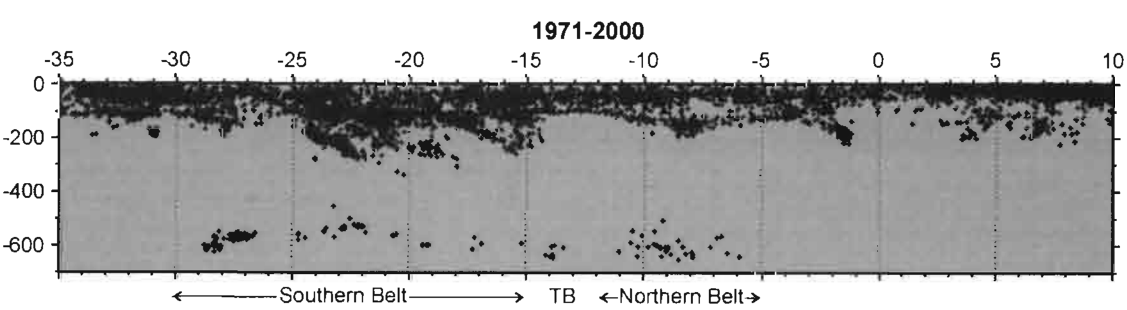

Figure 5. Longitudinal section of Andean seismicity between latitudes 35° S and 10° N

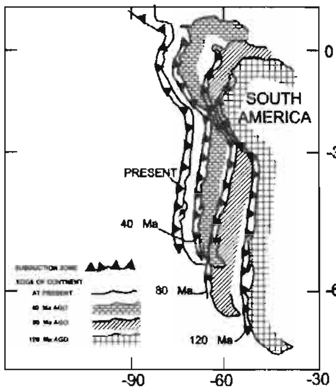

Figure 6. Absolute drift of Andean subduction zone since 120 Ma (Ref. Garfunkel et al., 1986)

energy release through brittle fracturing as in the case of the surface focus earthquakes. This happens despites the slab being continuous down to depths deeper than 500 km (Engdahl et al., 1995), the zone of deep earthquakes, which for the same reason their energy release cannot be attributed to brittle fracture. This means the kind of energy accumulation and the release mechanisms of deep earthquakes must be different from those earthquakes with h<300 km of depth, involving also large amounts of energy to provoke earthquakes with magnitudes larger than M_W 8.0. According to the hypothesis of top-to-N-NW shear of subducted Nazca plate, that different mechanism and source of energy for deep South American earthquakes could be the resistance that the deepest part of the slab finds to accompany the upper one migration towards N-NW. As a result, each time that resistance is overtaken there will occur a deep earthquake.

Focal mechanism solutions for some South American deep earthquakes indicate the rupture occurs in shear planes (Fukao, 1972) that are oriented in the slab direction. Focal mechanism of 07.31.1970 deep earthquake with epicentre in Peru-Colombia border region was represented by a rupture plane of 100x50 km^2 propagated for around 100 km southwards, almost normal to subducted plate, and dips steeply to west (Estabrook, 1999). A movement dominantly parallel to the fault plane dip direction, which is almost horizontal with 50x40 km^2, represents the focal mechanism of deep Bolivian earthquake of 06.09.1994, which occurred in Transverse Belt of deep earthquakes. In that belt subducted Nazca plate is oriented almost E-W, and has been dislocated northwards for almost 50 km (Wu et al., 1995; Beck et al., 1995). The direction of fault propagation in those earthquakes is in agreement with the overall direction of displacements postulated by the top-to-N-NW shear subducted Nazca plate hypothesis, although the southern propagation of faulting during the 1970 deep earthquake in opposite direction might be a particular result of events located in a probable extension of the subducted slab.

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