THE ANDEAN SUBDUCTION ZONE BETWEEN 22°S AND 25°S (NORTHERN CHILE): PRECISE GEOMETRY AND STATE OF STRESS

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RESUME : Un an d'enregistrement microsismique au Nord-Chili a permis de mieux préciser la géométrie de la subduction andine entre 22°S et 25°S et d' analyser l'évolution du régime de contraintes à profondeur superficielle et intermédiaire. L'interface entre les deux plaques en contact est sismiquement couplé jusqu'à la profondeur de 50 km. La relation entre cette profondeur critique et le champ de contraintes est discutée.

KEY WORDS : Subduction geometry, Stress field, Faulting, Seismic coupling.

INTRODUCTION

A permanent telemetric seismological network has been installed in june 1990 in the surrounding of the Antofagasta city and the Mejillones peninsula (northern Chile), in the geografical place of what can be considered the southern end of the great 1877 earthquake rupture zone. The operating of the network gives the opportunity to improve the knowledge of the present state of the subduction zone and to study the temporal evolution of the seismic activity in the area where the rupture of a great earthquake may initiate in the near future. The present work describes results obtained from the analysis of about one year (june 1990 - august 1991) of locally recorded microseismicity. As a first objective, more precision about the geometry of the Wadati-Benioff Zone is looked for. Then, the characteristics of the stress field and its variations along the subducting slab are investigated. Special attention is given to the caracterisation of the transition between underthrusting at the plate interface and the deeper intra-slab faulting.

METHOD AND DATA PROCESSING

The hypocenters are located with the HYPOINVERSE program (Klein, 1978). The crustal velocity structure is represented by a model of flat homogeneous layers based on seismic refraction profiles (Schmitz, 1991). The average crustal velocity for P wave is 6.6 km/s and the depth of the Moho is set to 48 km. The mantle velocity is taken to be 7.9 km/s. Travel times are corrected for the elevation of the stations. The Vp/Vs ratio was determinated from Wadati plots. So as to minimize the effect of dependance of the final hypocentral solution with the initial (trial) solution, each earthquake is localised with different trial depths. Trial depth is varied from 1 to 280 km with a 10 km increment. We retain as the "best" solution the one combining low RMS and the higher possible number of P and S arrivals taken into account. In order to avoid bad quality and poorly constrained hypocenters we submitted the hypocentral determinations to a sorting based on the following criteria: RMS inferior or equal to 0.25, total number time arrivals (P and S) taken into account greater or equal to 7, number of S-phases superior or equal to 2, computed horizontal and vertical errors inferior or equal to 5 km. Using the selection criteria indicated above, and restricting the latitude to the 22°20'S to 24°40'S interval, we obtained 412 hypocenters over the period june 1990 - august 1991. We present the distribution of the epicenters in Figure 1 and an EW cross-section in Figure 2.

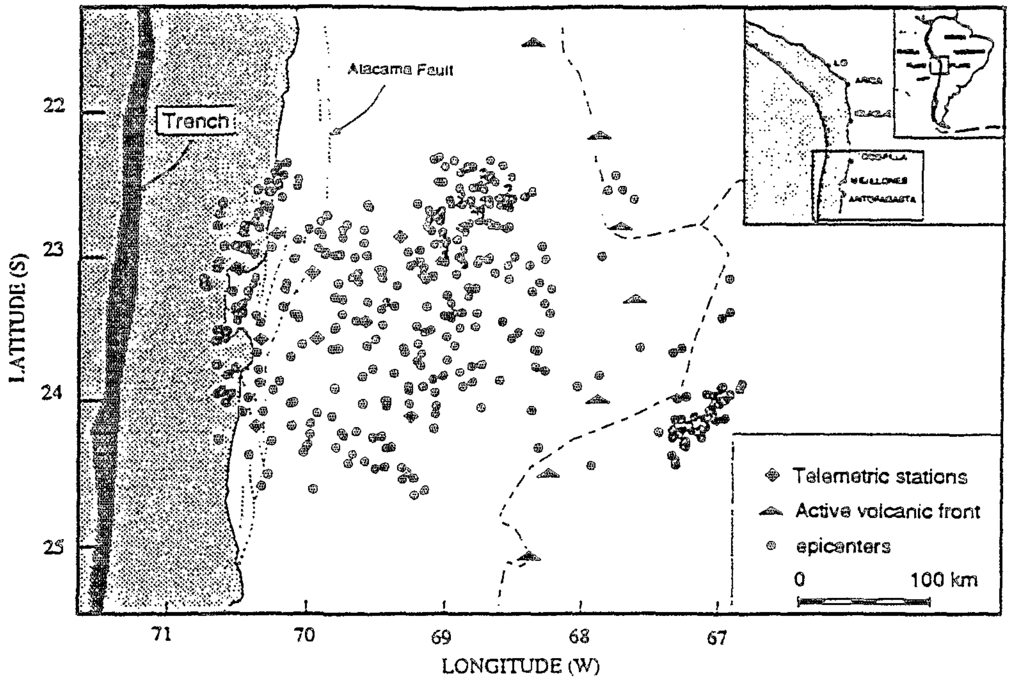

Figure 1. Epicentral map of the 412 selected earthquakes locally recorded during the period june 1990 - august 1991. The selection criteria is detailed in the text.

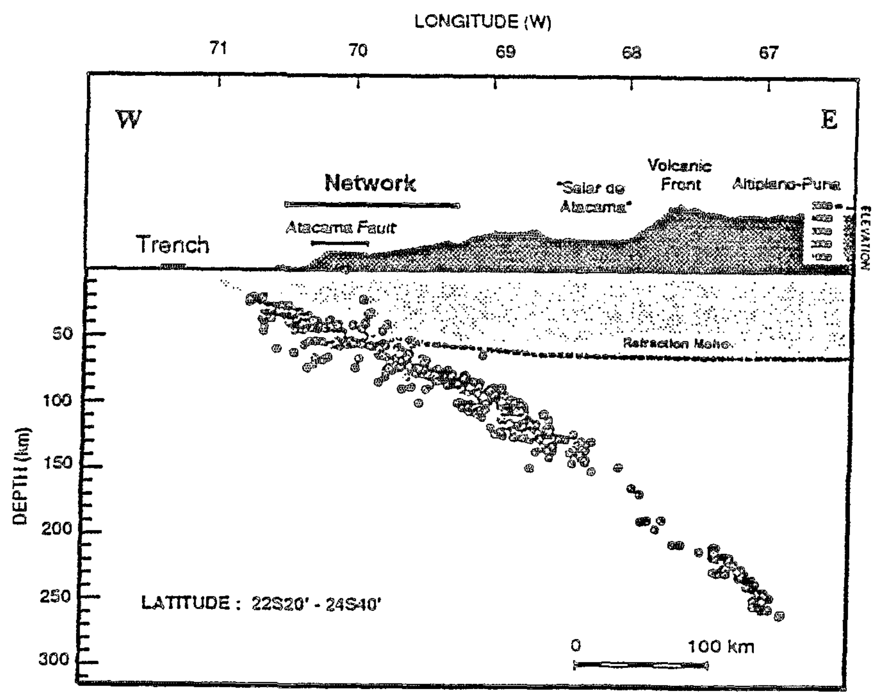

Figure 2. E-W cross section showing the hypocentral location of the 412 selected earthquakes locally recorded. The topografic profil in dark gray is taken at latitude 23°S15'. The refraction Moho is from Schmitz (interpreted seismic profil at latitude 24°S15', 1991). The shaded area above the Moho (light gray) and its prolongation towards the trench represent the continental crust.

In order to specify the stress field and the geometrical characteristics of the faulting along the subducted slab, we used an algorithm which provides simultaneous inversion of the orientation and shape of the stress tensor and of individual focal mechanisms for a population of earthquakes (Rivera and Cisternas, 1990). The method assumes that the stress tensor is locally homogeneous over the area of study. The avantage of the method is that we obtain the stress tensor not from previously and individually determined focal mechanisms which contain a certain degree of arbitrary choice, but rather from the original data of first motion polarities. The best way to detect variations in the stress regime in the Wadati-Benioff Zone is to define a sliding window along the slab. We limited our investigation to the upper part of the slab (longitude>69°, depth<100 km). Deeper earthquakes are too distant from the local network to permit a good enough constrain of their focal mechanisms. So as to rely on the most trustworthy data, we tested the stability of the hypocentral locations and the focal mechanisms with different velocity models.

RESULTS

Almost all earthquakes are located along a narrow tongue of concentrated sismicity related to the subduction of the Nazca plate, i.e. defining a sharp Wadati-Benioff Zone (WBZ, see Figure 2). The upper limit of the WBZ is particulary well defined. The WBZ dips with an angle of 17°-18° up to about 100 km depth. The deeper part of the slab dips more steeply but we observe a systematic displacement of our hypocenters in the downward-westward direction relative to the world wide recorded teleseismic events below 100 km depth (Cahill and Isacks, 1992). Lareral heterogeneities, in particular the slab/mantle velocity contrast, not taken into account in the velocity model, may explain such discrepancy (McLaren and Frohlich, 1985). A seismically quasi-quiescent zone is observed below 150 km depth, under the volcanic arc. Deeper events occur mainly in a clustered form at 200-260 km depth. Synthetics tests proved that the quiescent zone cannot be an artificial gap produced by the location process and that the sharp definition of the deep cluster is not an artificial concentration of hypocenters. The intermediate depth quiescent zone is a characteristic feature of the WBZ along southern Peru and northern Chile. A strong concentration of intra-slab seismicity is generally observed updip of the quiescent zone and is possibly related to the effective deshydratation of the oceanic crust and to the phase transformation from basalt to eclogite. Those mechanims are supposed to activate faulting (Liu, 1983; Haak and Giese, 1986). The onset of the quiescent zone may correspond to the limit beyond which those mechanisms end, and/or may be related to the proximity of the asthenospheric wedge below the volcanic front.

The inversion of the stress tensor and the focal mechanisms for different depth range along the WBZ give very coherent results. From 20 km to 50 km depth we observe only underthrusting earthquakes with a north-south nodal plane dipping sligthly towards the East (Figure 3). Although the rupture and the seismic moment release of great interplate earthquakes may extend further down, those underthrusting microearthquakes indicate that the seismogenic part of the interface ends at 50 km depth. Downdip, intra-slab normal faulting prevails. Normal faulting, rather heterogeneous first, becomes very homogeneous at about 80-100 km depth (Figure 3). It is then characterized by a vertical or east steep dipping nodal plane of NNW to NW orientation.

Over the full range of depth investigated (20-100 km) the stress field is characterized by a minimum principal stress σ_3 oriented in the mean azimut 070°. The intermediate principal stress σ_2 is horizontal and strikes in the azimut 335°. Below 50 km depth, where normal faulting plus a few strike-slip faulting occur (Figure 3), the stress regime is extensional and σ_3, which is low dipping, can be related to the slab pull force. Above 50 km depth, where underthrusting occur, the dip angle of σ_3 is loosely constrained and may vary from 35° to 70°. Underthrusting focal mechanisms can be so well explained by a σ_3 low dipping or by a σ_3 steep dipping. Two different scheme may be proposed as possible interpretations for the evolution of the stress regime along the WBZ, depending on the dip angle of σ_3 in the underthrusting zone.

If σ_3 is steep dipping (70°), then σ_1 dips only slightly (20°) in the azimut 255°. Then, the stress regime is compressional at the locked plate interface, as it is generally assumed, and the compression expresses the convergence between the two plates (azimut 075° or 255°). In that case, the stress field would invert abruptly at the depth of 50 km.

Conversely, if σ_3 has a much greater horizontal component, dipping only 35° in the azimut 075°, we have an alternative scheme in which the slab pull force acts also at superficial depth in the locked segment of the slab, beeing possibly the dominant force there. This alternative is supported by the occurrence of tensional earthquakes beneath the underthrusting interface (Malgrange and Madariaga, 1983, Comte et al., 1992, NEIC). In the present study, one tensional event has been located 100 km east of the trench, 15-20 km beneath the coupled interface. Thus, the transition between interplate underthrusting and intraplate normal faulting would not necessarily suppose a drastic change in the stress regime, but would essentially reflect the change in the mechanical behaviour of the interface which would undergo a unstable-stable slip transition

Some deep crustal seismic activity (20-50 km depth, see Figure 2) is observed locally at the deep root of the Atacama Fault. The pertubation of the thermal structure of the lower continental crust related to the proximity of the cold slab could explain the occurrence of seismic rupure at such depth.

The lower limit of the coupled-seismogenic part of the plate interface has been located precisely at 50 km depth. The transition from underthrusting at the plate interface and intra-plate normal faulting takes place over a very short distance along the slab. Strike-slip faulting occurs in between (Figure 3), immediately downdip of the coupled zone and may indicate that the slab, once unlocked from the overriding plate, undergoes some left lateral motion in response to the obliquity of the convergence. The coupled-uncoupled transition occurs approximatively at the depth where the WBZ and the Moho seem to diverge (Figure 3), suggering that a relation exists between seismic-coupling and the presence of continental crust at the plate interface.

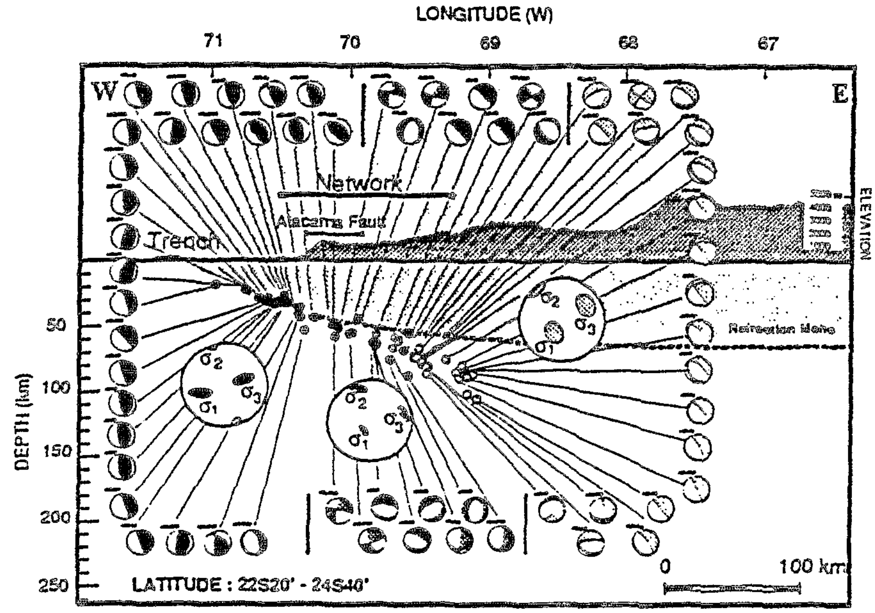

Figure 3. Focal mechanisms and the stress field along the Wadati-Benioff Zone (WBZ) up to 100 km depth. The WBZ has been divided into three consecutive segments corresponding to different depth ranges (dark gray, medium gray and light gray). In each segment the focal mechanisms and the stress tensor have been inverted from the first motion polarities using the Rivera-Cisternas algorithm (1990). Focal mechanisms are represented on the lower hemisphere equal area projection and the shaded areas are the compressional quadrants.

REFERENCES

Cahill T. and Isacks B. L., 1992 - Seismicity and shape of the subducted Nazca plate. - J. *Geophys. Res.*, 97, 17503-17529.

Comte D., Pardo M., Dorbath L., Dorbath C., Haessler H., Rivera L., Cisternas A. and Ponce L., 1992. - Seismogenic interplate contact zone and crustal seismicity around Antofagasta, northern Chile, using local data. - *submitted.*

Haak V. and Giese P., 1986. - Subduction induced petrological processes as inferred from magnetotelluric, seismological and seismic observations in N-Chile and S-Bolivia. - *Berliner Geowiss. Abh.*, (A), 66, 231-246; Berlin.

Klein F. W., 1978. - Hypocenter location program HYPOINVERSE, *U.S. Geol. Surv., Open File Rep.*, 78-694.

Liu L-g, 1983. - Phase transformations, earthquakes and the descending lithosphere. - Phys. Earth Plan. Int., 32, 226-240.

Malgrange M. and Madariaga R., 1983. - Complex distribution of large thrust and normal fault earthquakes in the chilean subduction zone. - *Geophys. J. R. Astr. Soc.*, 73, 489-505.

McLaren J.P. and Frohlich C., 1985. - Model calculations of regional network locations for earthquakes in subduction zones. - *Bull. Seismol. Soc. Am.*, 75(2), 397-413.

Rivera L. and Cisternas A., 1990. - Stress tensor and fault plane solutions for a population of earthquakes. - *Bull. Seismol. Soc. Am.*, 80(3), 600-614.

Schmitz M., 1991. - *Pers. comm.*