QUATERNARY DEFORMATION ALONG THE CHILEAN ACTIVE MARGIN RELATED TO OBLIQUE CONVERGENCE

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Summary

Kinematic analysis of fault slip data for stress determination was carried out on Neogene and Quaternary rocks from the fore arc and intra-arc regions of the Chilean Andes and part of the Bolivian Andes. These studies have revealed various states of stress.

Introduction

The Chilean Andes are located above a subduction zone whose convergence vector trending N79°E is oblique to the plate boundary. Between 27° to 33°S, the subduction is sub-horizontal and modern volcanism is absent. South of 33°S the angle of subduction is 30° and modern volcanism appears as far as the Chilean Ridge Triple Junction (CTJ) (46°30S) (fig. 1).

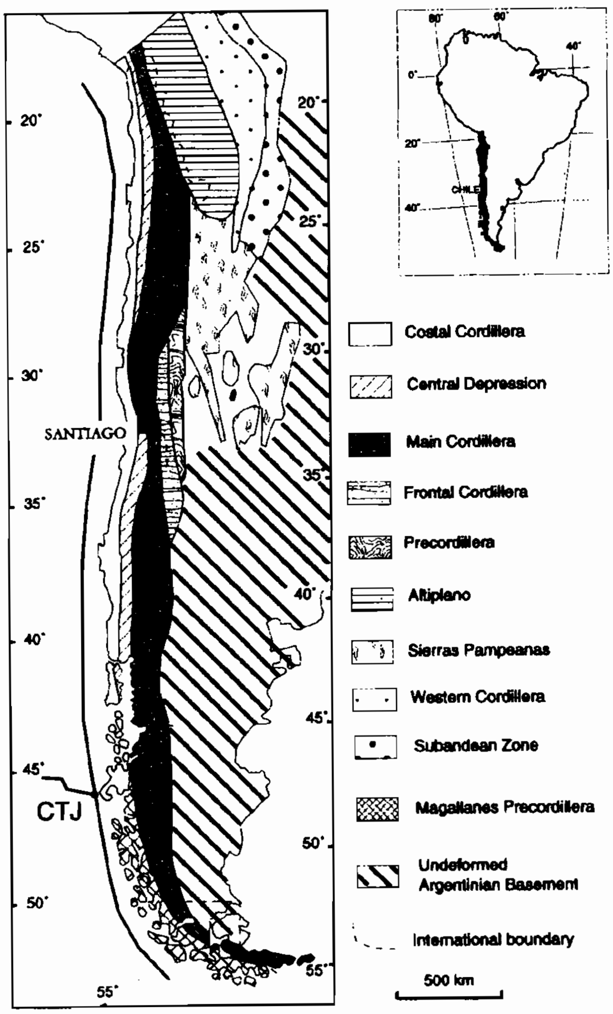

Fig. 1 Morpho-structural units and structural provinces of the southern Andes.

Between 33° and 46°S the continental fore arc is characterized by the presence of the Coastal Range and the Central Depression, parallel to the Cordillera. This depression starts in the north, in the region of Santiago, and ends to the south of Aysen, in the Ofqui Isthmus, at the latitude of the CTJ. It extends for more than 1000 km, with a width that does not exceed 75 km. Between 38° and 46°S, the eastern limit of the Central Depression merges with the volcanic arc along which the Liquiñe-Ofqui Fault Zone (LOFZ) (cf. fig.5) has developed. This fault zone, one of the largest active strike-slip fault zones of modern subduction (e.g. Jarrard, 1986) extending more than 950 km in length, represents one of the main lineaments of Chile.

Between 39°S and 41°30'S, east of the LOFZ, the Main Cordillera, which appears as uplifted blocks of basement, can be explained by "pop up" as described in Argentina by Diraison *et al.* (1998).

Fig. 2 Quaternary reverse fault and drag fold near Santiago (San José de Maipo, Cordillera Principal).

Quaternaire Compressional Tectonics

Between 32°S and 47°S, from the coast to the Main Cordillera or the Cordillera Principal, the microfracturing analysis allow us to calculate a N-S to NE-SW trending compressional stress direction posterior to the Pliocene (post 2.8 Ma in Central Chile): along the coast, near San Antonio and in Chiloe Island; in the Central Depression [Esperanza, Victoria, Fresia]; in the Cordillera Principal [Santiago, San José] (fig. 2). In these sites, the compressional stress direction is roughly N-S ($\sigma 1$ horizontal and trending N10°E ± 22°) (fig. 3).

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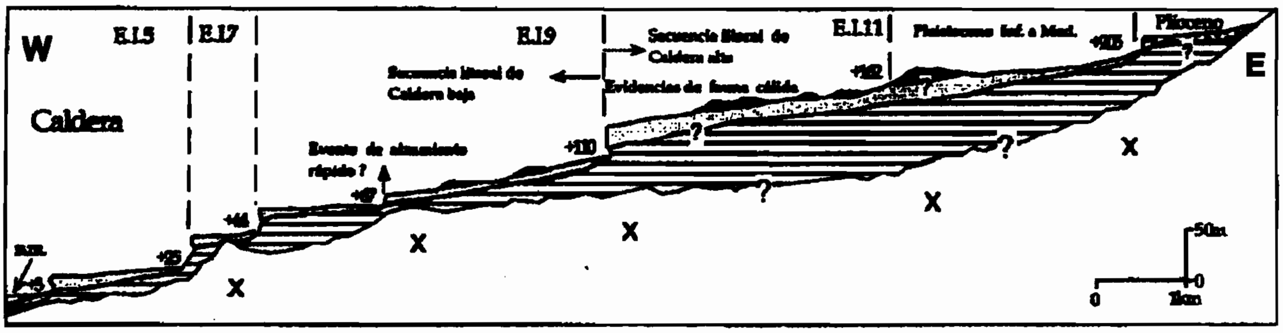


Fig. 6 Main terraces and associated deposits in the Caldera area (after Marquardt, 1999). Location of the main coastal lines. The chronological interpretation is founded on the Quaternary isotopic stages.

faults (fig. 7), probably coseismic, which may be related to reactivation of pre-existent structures. The Quaternary regime is extensional with a roughly E-W direction. Based on their trend and the age of the deposits involved in the deformation, a later date than 125 kyr is proposed for the extensional brittle structures (Marquardt and Lavenu, 1999). This deformation characterizes the westernmost portion of the continental fore arc, close to the trench axis (~ 80 km), and does not appear to be directly linked to boundary forces due to the convergence, but could be the consequence of co-seismic crustal bending with subduction-related earthquakes. It could be due to topographic accomodation to the uplift of this part of the coast (body force due to topography): $\sigma 3$ striking E-W, $\sigma 2$ striking N-S, and $\sigma 1$ vertical.

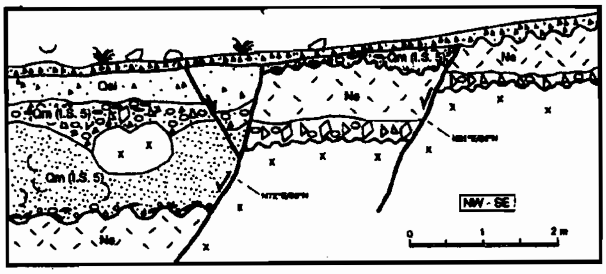


Fig. 7. Quaternary normal faulting near Caldera (27°S) resulting to a NNW-SSE extension (Marquardt and Lavenu, 1999).

In the Bolivian High Andes, (Lavenu and Mercier, 1991) from the Lower Pleistocene to the Present, the whole range is affected by an extensional tectonics with $\sigma 3$ N-S trending (kilometric normal faults with hectometric throw) (fig. 8, 9). In the Altiplano and the High Andes, Quaternary tectonic regime is extensional with $\sigma Hmin = \sigma 3$, N-S trending, $\sigma Hmax = \sigma 2$, E-W trending and $\sigma 1$ vertical. In Perú, in the Western Cordillera and Altiplano, recent and active deformations result also from N-S trending extensional tectonics (fig. 10). In Bolivia, as in Peru, this stress field results from body forces due to a compensed high topography. The E-W trending horizontal stress $\sigma Hmin = \sigma 2$ is roughly parallel to the convergence direction. σzz ($\sigma 1$) increase with the topography due to the range weight. In the Eastern Cordillera, the intermediate zones (e.g. Tarija, 1900 m in elevation) are characterized by two superposed stress regimes. One is a relatively weak strike-slip compressional stress, with $\sigma 2$

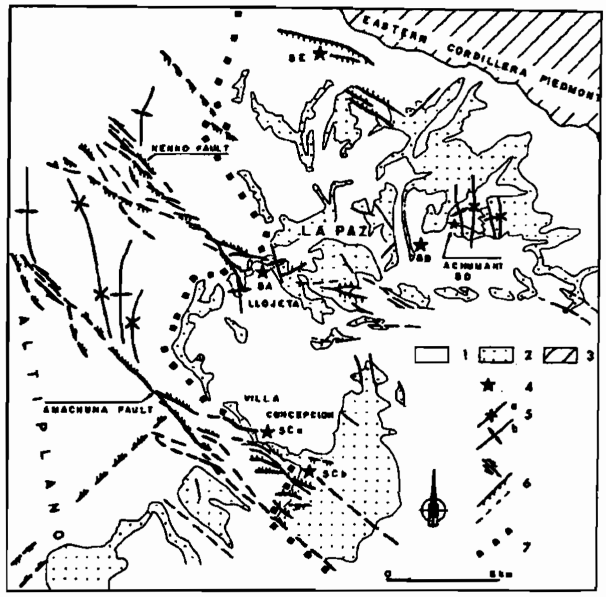


Fig. 8 Schematic structural map of the La Paz region, Bolivia. 1- Quaternary rocks; 2-Pliocene deposits; 3-Pre-Pliocene deposits; 4- Studied sites; 5- anticinal and synclinal; 6-faults, 7-Morphological edge of the Altiplano (Lavenu and Mercier, 1991).

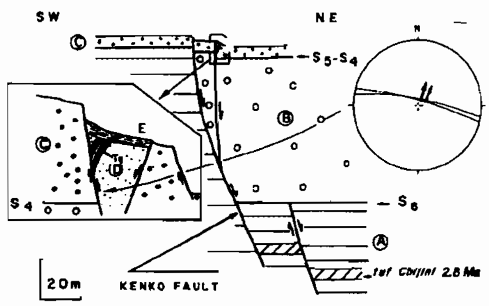
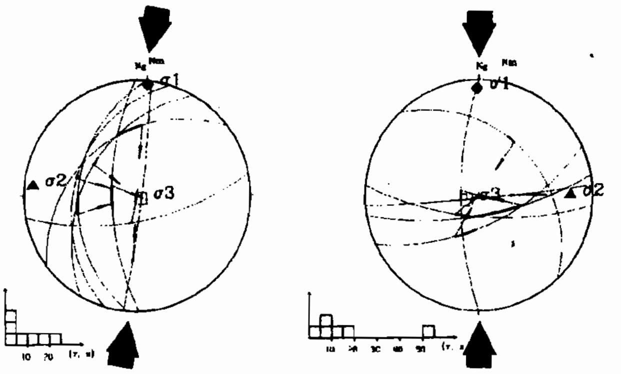


Fig. 9 Cross section of the Kenko normal fault, La Paz, Bolivia (Lavenu and Mercier, 1991).A: Pliocene; B,C,D: Quaternary; S4, S5,. S6: erosional surfaces.

In the magmatic arc, and along the Liquiñe-Ofqui Fault, the compressional stress direction is NE-SW, and the tectonic regime is transpressive (σ1 horizontal and trending N42°E ± 20°, σ3 perpendicular and horizontal) posterior to 1.6 Ma in Southern Chile [Puyuhuapi].



Site 25, Northern area (fore arc) Site Esperanza, Central area (fore arc)

Fig. 3 Slip vector data from Quaternary reverse faults of the Chilean Main Cordillera (San José, site 25, cf. Fig. 2) and the Central Depression (site Esperanza).

Quaternary Extensional Tectonics

In some areas of the narrow Chilean coastal belt (Mejillones-Antofagasta, Caldera, La Serena-Coquimbo, the Arauco Peninsula) sequences of marine terraces are preserved between 0 and 250 to 300 m a. s. l. (fig.6). The Quaternary deposits are deformed by variously oriented high angle normal

Fig. 4 Morphological feature of the normal Atacama fault near El Salar del Carmen, Antofagasta.

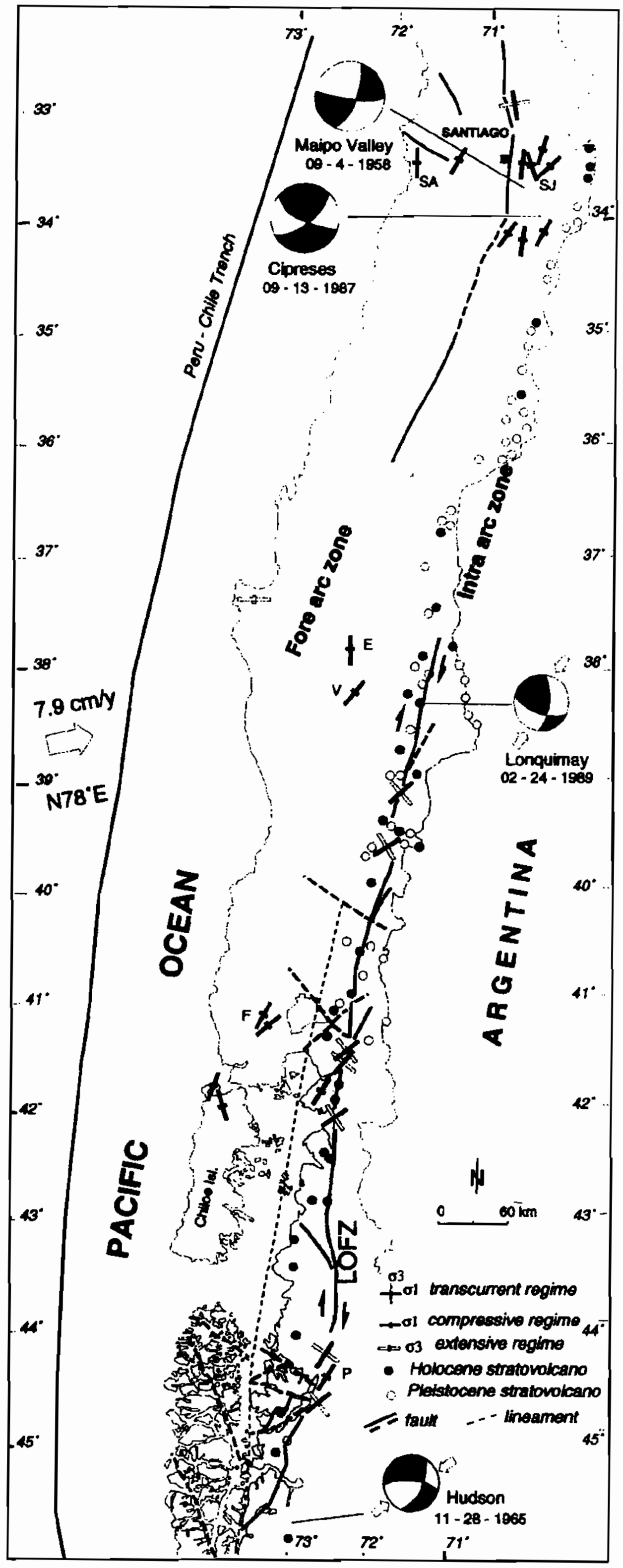


Fig. 5 Principal directions of the maximum horizontal compressional stress σ1 deduced from microtectonic analysis of Quaternary faults of the Andes of Central and Southern Chile (SA: San Antonio, SJ: San José, E: Esperanza, V: Victoria, F: Fresia, P: Puyuhuapi) (after Lavenu and Cembrano, 1999).

vertical, σ1 = σHmax, E-W trending, and σ3 = σHmin, N-S trending. The other one, more intensive, is an extensional axial stress, with σ1 vertical. σ2 trends E-W and is equivalent to σ3 which trends N-S. If we admit that the vertical stress σzz is the result of the weight of an isostatically compensed topography, the strike-slip state of stress is consistent with the intermediate location of the basin, between the subandean zone and the high Andes.

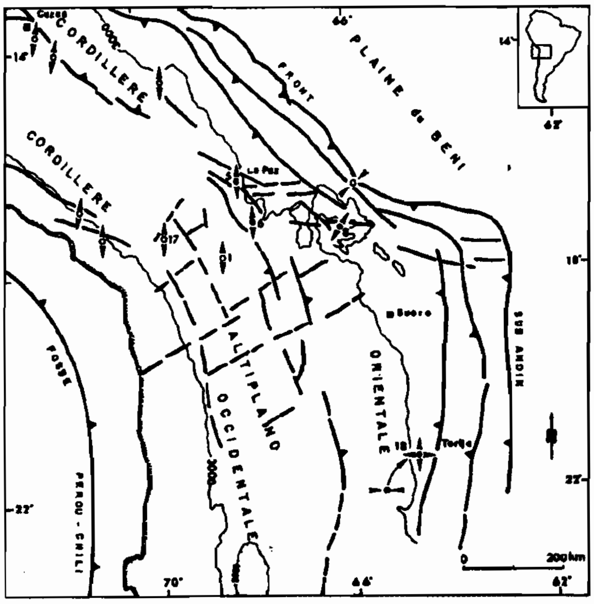


Fig. 10 Main tensional directions deduced from structural analysis of Quaternary faults from Bolivia (Lavenu and Mercier, 1991)

Conclusion

The study of the recent state of stress in the Central and Southern Andes evidences several behaviors of the continental plate along the active margin. These behaviors are linked to the dip of the subducted plate, the obliquity of the convergence between the oceanic and continental plates, the body forces and the boundary forces, the presence or absence of buttress zones in the upper plate, and the possibility that the coastal blocks have a free northward escape (fig. 11). The analysis of the recent brittle deformation in the fore arc and intra-arc zones in the Andes of Central and Southern Chile between 33° and 46°S allows us to demonstrate the existence of a partition of maximum horizontal compressive stress (σHmax) directions, characterized by a N-S (fore arc zone) to NE-SW (intra-arc zone) compression. Actually, during the Quaternary, and after 2.8-1.6 Ma, two different states of stress are evidenced; one of a N-S to NNE-SSW direction in the fore arc zone, the other of a NE-SW direction, in the volcanic arc zone along the LOFZ. The N-S Quaternary compression in the fore arc, linked to a slower convergence regime with a certainly weaker coupling, can be also explained by different factors such as the geometry of the plate margin and/or abrupt changes in subduction geometry. The fact that Quaternary deformation is weak in both the fore arc and arc regions between 33° and 46°S can be explained by the accomodation of large amounts of plate convergence within the Benioff zone through large-magnitude earthquakes, such as the Valdivia 1960 event. This earthquake accomodated slip was equivalent to more than 500 years of convergence (e.g. Plafker and Savage, 1970). Along the coast, the areas closest to the trench are affected by an E-W extensional tectonic regime.

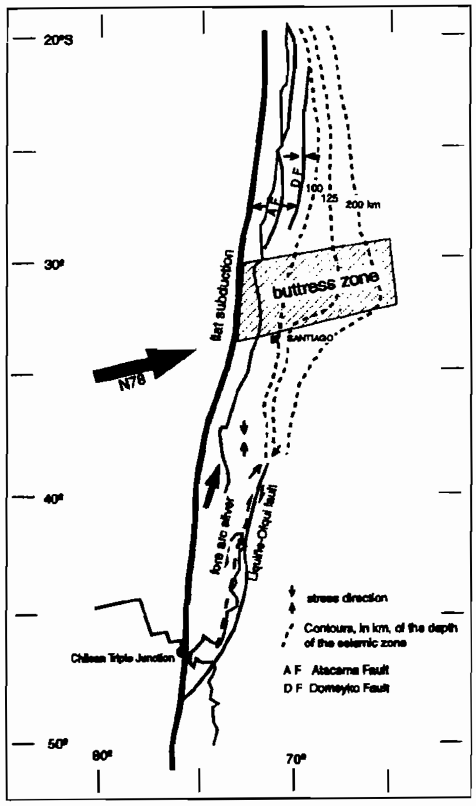


Fig. 11 Potential north trending motion of the fore arc sliver.

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The Chilean Andes are situated above a subduction zone whose convergence vector is oblique to the plate boundary. The different ways by which this accomodation is achieved are problematic, especially the relation between subduction and deformation of the overriding plate. In coastal areas that are closest to the subduction trench (about 80 to 100 km offshore) the state of stress from upper Pleistocene until present is E-W extension. Neotectonic observations and structures compiled in the framework of the World Map of Major Active Faults (ILP Project II-2) show that the recent deformation is essentially characterized by vertical uplift and subsidence related to normal faulting (e.g. the Mejillones Peninsula faults, and Paposo and Salar del Carmen segments of the Atacama fault). This long-term extension is related essentially to the uplift of the Andes chain, as evidenced by uplifted marine terraces, and to the great thrust earthquakes along the interplate Waditi-Benioff zone, which are a direct consequence of the subduction. South of 32°S, the deformation is partitioned into two distinctive states, whereas north of Santiago (33°S) the Quaternary state of stress of the forearc is still unknown. In the forearc sliver, Coastal Cordillera, Central Depression and part of the Main Cordillera, compressive deformation occurs with sigma 1 trending N-S and sigma 3 vertical. In the intra-arc, compressive strike-slip deformation (transpression) occurs with sigma 1 NE-SW and sigma 3 NW-SE. This results in a N-S compressional state of stress that could be related to the effect of deformation partitioning which generates the northward displacement of the forearc sliver, along the Liquine-Ofqui Fault Zone. In the Magallanes region (southern Patagonian Andes), the plate interaction generates left lateral movement along regional-scale faults (Rio San Juan and Lago Fagnano).