AN AREA-BALANCED MODEL OF THE LATE CENOZOIC TECTONIC EVOLUTION OF THE SOUTHERN BOLIVIAN ARC AND BACK-ARC

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INTRODUCTION

Newly available geological and geophysical data yield new constraints on the late Cenozoic evolution of the southern Bolivian central Andes (Fig. 1) and motivate re-evaluation and refinement of former tectonic models (e.g. Suàrez et al., 1983; Isacks, 1988; Roeder, 1988; Sheffels, 1990; Schmitz, 1992). The main purpose of this effort is to quantitatively unravel the detailed tectonic evolution in consistency with geological and geophysical data at hand. Such a model allows to study the relevance of other processes suggested for Andean orogeny, i.e. thermal uplift (Froidevaux & Isacks, 1984) and magmatic addition (Thorpe et al., 1981; de Silva, 1989). Furthermore, the model provides a guideline for further quantitative modelling studies in which the thermal and mechanical aspects of the suggested tectonic model can be examined.

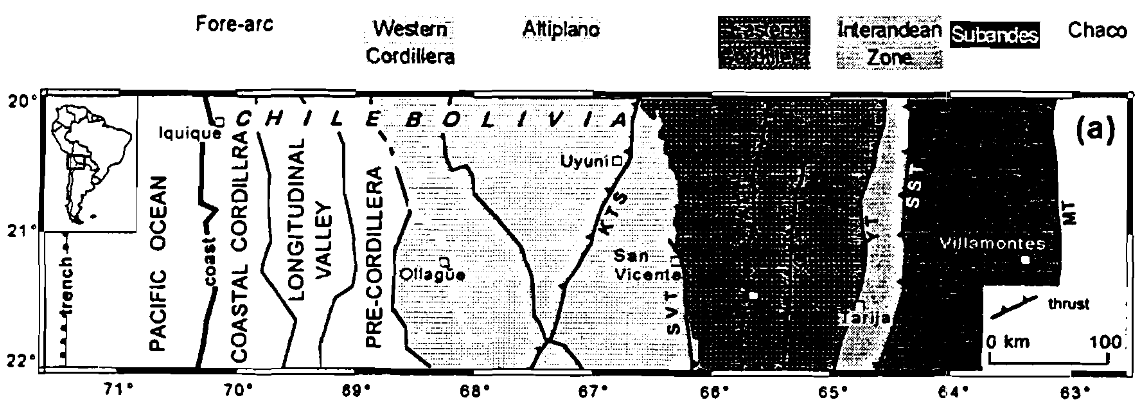

FIGURE 1: Map of the 20°-22°S section of the Central Andes showing the main tectonic units, and major thrusts in the region between the Altiplano and the Chaco (KTS: Khenayani Thrust System; SVT: San Vicente Thrust System, ATT: Aquile-Tupiza Thrust, CTT: Camargo-Tojo Thrust, YT: Yuncharà Trust, SST: San Simón Thrust; MT: Mandeyapecua Thrust).

METHOD & DATA BASE

Based on different geological and geophysical data a plausible scheme of the crustal evolution from late Oligocene to present (27-0 Ma) along an idealised cross-section reaching from the Western Cordillera to the Chaco foreland (20°-22°S) (Fig. 1) is synthesised in an area-balance model. The tectonic evolution is described by relating upper-crustal thrusting to crustal-scale deformation. The amount of isostatic uplift is included by Airy isostasy. The reordered upper crustal convergence is balanced by a corresponding mantle-lithospheric shortening. In the model thermal and rheological arguments are used to distinguish between pure and simple shear deformation.

The model is constraint by and tested against the following geological and geophysical data. Estimates of upper crustal shortening together with age data (e.g. Baby et al., 1992, 1990, 1989; Gubbels et al., 1993; Kley, 1996; Kley et al., 1996) supply the detailed deformation history along a continuos section through the southern Bolivian Andes. Evidence on the timing of crustal thickening along the profile is derived from data on the uplift history (e.g. Jordan & Alonso, 1987; Sempere et al., 1990; Gubbels et al., 1993). The present-day deep seismic structure (Wigger et al., 1993) yields clues to tectonic processes at depth and confines the crustal structure of the model at 0 Ma. The magmatic activity (Davidson et al., 1990; Avila-Saliñas, 1991) is associated with a region of thinned mantle-lithosphere (Isacks, 1988).

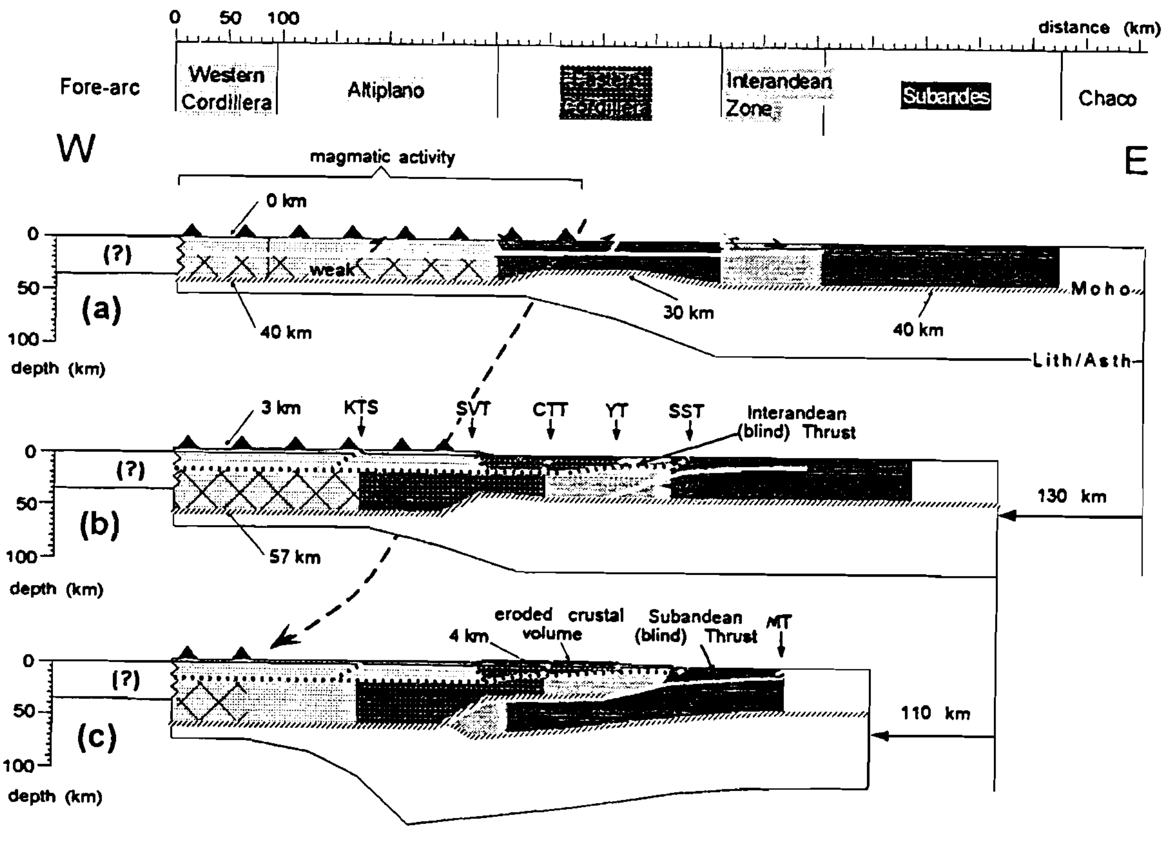

FIGURE 2: Area-balanced model of the 27-0 Ma phase of the tectonic along an idealised cross-section reaching from the Western Cordillera to the Chaco foreland. The Figure shows snapshots of the model (a) at 27 Ma, (b) at 5 Ma, and (c) at 0 Ma. Motions are indicated by black half arrows; active thrusts are shown in white lines, inactive thrusts are shown in dashed black-white lines. The area of magmatic activity is outlined by black triangles. The hatched line indicates the initial Moho at 27 Ma followed through time.

AREA-BALANCED MODEL OF THE TECTONIC EVOLUTION

At the on-set of deformation (~27 Ma) the initial state of the Chaco, the Subandes, the Interandean Zone, the Altiplano and the Western Cordillera (Fig. 2a) is characterised by a largely uniform crustal thickness of 40 km (Isacks, 1988, Schmitz, 1994). The eastern part of the Eastern Cordillera is assumed to mark the eastern transition to the thinned, 30 km thick crust of the western Eastern Cordillera where Cretaceous rifting events are documented (e.g. Avila-Salinas, 1991). The width of the individual tectonic units is restored according to the recorded shortening amounts. These are in the Altiplano ~20 km (Baby et al., 1990), at the western margin of the Eastern Cordillera ~35 km (Kley et al., 1996; Baby et al., 1990), in the Eastern Cordillera ~30 km (Kley et al., 1996), in the Interandean Zone ~45 km (Kley, 1996), and in the Subandes ~110 km (Kley, 1996; Baby et al., 1992, 1989). The thinned mantle lithosphere of ~10 km thickness corresponds to the area of late Oligocene magmatism reaching from the Western Cordillera to the western Eastern Cordillera; further east the mantle-lithospheric thickness amounts to ~60 km.

Based on the data summarised above the late Cenozoic tectonic evolution of the southern Bolivian Andes is suggested to be due to two major thickening mechanisms for crustal convergence.

During the ~27-5 Ma phase (Fig. 2a and b) upper crustal shortening of ~130 km in the Altiplano, the Eastern Cordillera and the Interandean Zone is adapted along a major detachment (future "Interandean blind thrust"; Kley, 1996) which follows the brittle-ductile transition at upper-crustal level beneath the Eastern Cordillera and at mid-crustal level beneath the Altiplano. At depth the cold (rigid) middle and lower crust of the Eastern Cordillera thrust under the Altiplano and the heated (ductile) lower crust of the Altiplano and the Western Cordillera thicken by pure shear. In the Western Cordillera and the Altiplano, this phase accounts for thickening (~57 km) and for major uplift (~3 km). The Eastern Cordillera is only affected by minor thickening (~40 km) and uplift.

During the ~5-0 Ma phase (Fig. 2b and c) a new major detachment ("Subandean blind thrust"; Kley, 1996) establishes. The Subandean crust thrust under the crust of the Eastern Cordillera by simple shear deformation. This process accounts for upper crustal shortening of ~110 km in the Subandean fold-thrust belt, and thickening, uplift and erosion in the Eastern Cordillera. This deformation could be responsible for the distinct change from rugged, deeply incised topography of the Eastern Cordillera to valley-and-ridge topography of the Subandean fault-thrust belt.

CONCLUSIONS

(1) In the suggested model the present-day crustal volume of the seismic structure is well reproduced east of the San Vicente thrust indicating that tectonic shortening played the dominant role in the eastern part of the orogen. West of the San Vicente thrust, under the Western Cordillera and the Altiplano, crustal volume is missing. This volume would correspond to an additional shortening of ~80 km in the area between the Altiplano, Eastern Cordillera and Interandean Zone.

(2) The model suggest that additional processes are responsible for crustal uplift and thickening in the Western Cordillera and Altiplano. Magmatic addition would require ~2500 km^2 of magma intrusion. Thermal uplift would demand delamination of the lower lithosphere at the eastern margin of the Altiplano. An update of the chronology of magmatic activity could yield constraints on the relevance of this processes in Andean orogeny.

(3) A distinct characteristic of the tectonic model is the different uplift mechanism for the Altiplano and Eastern Cordillera. The Western Cordillera and Altiplano rose uniformly by pure shear thickening of the lower crust whereas the Eastern Cordillera uplifted stepwise with inception at its eastern border and westward migration with time. Geochronological data giving constraints on the timing and amount of exhumation are necessary to confirm this pattern.

(4) In comparison with the model by Isacks (1988) and Gubbels et al. (1993) our model accounts for the observed Interandean and Subandean thrusts (Kley, 1996). The "Quechua" phase (~14-10 Ma) leading to compressive deformation in the Altiplano (Jordan & Gardeweg, 1989) affects in southern Bolivia the eastern Eastern Cordillera whereas deformation in the Altiplano is predated to ~27-19 Ma.

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