Numerical plan view restoration of the Bolivian Orocline

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INTRODUCTION

In map view, the Central Andes are arcuate. The bend (through 55°) is known as the Bolivian Orocline or Arica-Santa Cruz Elbow (Figure 1). It is associated with a remarkable pattern of rotations about vertical axes. In previous studies, it has been assumed that, in the Central Andes, (1) most of the shortening is Neogene in age and (2) mainly it has occurred in the Eastern Cordillera and Subandean-Santa Barbara Zone [see summaries by *Kley and Monaldi*, 1998]. From the trench to the leading edge of the fold-and-thrust belt, the total shortening is estimated to be >320 km. It could account for as much as 70%–80% of the observed crustal volume, the remainder being due to magmatic addition or tectonic underplating. Alternatively, pre-Neogene shortening could account for the discrepancy. Some authors have argued that regional shortening started during the Late Cretaceous or Early Paleocene [e.g., *Horton et al.*, 2001], whereas others have contended that regional shortening did not begin until the Eocene [*McQuarrie and DeCelles*, 2001]. According to recent dating of fission tracks in apatite, Andean shortening reached the northeastern Puna towards the end of the Eocene and the adjacent Eastern Cordillera towards the end of the Eocene or beginning of the Oligocene [*Coutand et al.* 2001]. In the central part of the Eastern Cordillera, after an initial uplift at ~58 Ma, the first thrusts developed in the Middle Eocene to Early Oligocene [*Müller et al.*, 2002]. Tectonic shortening culminated in Late Oligocene and Early Miocene time (25–20 Ma), when west-facing thrust systems developed in the central and western parts of the Eastern Cordillera. In the western part, thrusting ended in the Early Miocene, and Middle Miocene tectonic activity was restricted to minor strike-slip faulting. In the central part, thrusting remained active until the Late Miocene. By about 10 Ma, shortening ceased in the Eastern Cordillera as thrusting migrated eastward to the Sub Andean zone [e.g. Gubbels et al, 1993]. More generally, deformation in the Central Andes is a combination of thrusting, wrenching and block rotations. The non-plane deformation cannot be restored properly using balanced cross sections alone. We have therefore adapted a method of restoration of non-plane deformation, which is based on least-squares fitting of fault-bounded blocks in map view [e.g. *Bourgeois et al.*, 1997]. Our objective is to restore the Bolivian Orocline, where shortening and block rotations are large.

CONSTRUCTION OF THE MODEL

To take into account the deformation that has accumulated in the Central Andes since the Eocene, we have constructed a block map of the Orocline between latitudes 5°S and 30°S, including the main segments of the chain between the Chile-Peru trench and the Brazilian craton, and the first-order fault and lineaments (Figure 1). At shallow crustal levels, volcanic and other superficial deposits commonly obscure deep-seated faults. The underlying structures can nevertheless be inferred from alignments of secondary features, such as stratigraphic discontinuities or facies changes, linear arrays of magmatic features (intrusions, volcanoes), or topographic features. In addition to major orogen-parallel structural corridors, the map shows several transverse lineaments (for example, the Calama–Olacapato–El Toro lineament), which can be traced from the Pacific coast of Chile, across the Cordillera Occidental, and into the Puna. Several of these lineaments coincide with southeastward-trending volcanic breakouts from the main arc, suggesting a structural control on magmatism. By extending some of the fault tips and adding a few minor faults, we have defined 191 fault-bounded blocks (Figure 1). Large and elongate blocks we have subdivided, by means of artificial straight boundaries. The restoration procedure minimizes all gaps and overlaps between the blocks. It takes into account available paleomagnetic rotations, shortening data from published balanced cross-sections, and shortening estimates based on available geological constraints.

RESULTS

Shortening in the Sub-Andean Zone (~40%) is not sufficient to change significantly the geometry of the margin (Figure 1). The total shortening displacement is 100-130 km at the latitude of Arica. Rotations are smaller than 10° in the fore-arc of Chile or Peru. To account for the large rotations in southern Peru prior to 15 Ma, our preferred model implies major Eocene to Early Miocene deformation, essentially in the Eastern Cordillera, and an additional 210 km of shortening at the latitude of Arica. The total shortening of 300-330 km, from the Eocene to the Present, is consistent with previous estimates of 310-340 km [*McQuarrie and DeCelles*, 2001; *Müller et al.*, 2002].

DISCUSSION

According to our plan view restoration, which takes into account available paleomagnetic data, oroclinal curvature of the Central Andes developed mainly in the Eocene to Early Miocene, in close relationship with the Eastern Cordillera. From the Middle Miocene to the Present, the Nazca plate was strongly coupled to the fore-arc [*Lamb and Davis*, 2003]. The rigid fore-arc acted as an indenter, resisting the westward absolute motion of the South American plate [*Tassara*, 2005] and transferring, with minimal internal deformation, the non-seismic component of convergence towards the east, in particular to the Sub-Andean Zone. Our preferred model has major oroclinal bending prior to the Middle Miocene and does not support claims of accelerating shortening associated to the decelerating convergence between the Nazca and South American plates during the last 10 Ma [*Hindle et al.*, 2002]. Recent robust estimates of shortening velocities from GPS data [*Kazaradze and Klotz*, 2003] are significantly less than 10 mm/yr in the back-arc. They therefore support the lowest estimate on shortening for the Middle Miocene to the Present in our preferred model of restoration.

Paleomagnetically determined rotations in Middle Miocene to Recent rocks are much smaller than the rotations determined for Eocene to Early Miocene and older rocks. Middle Miocene to Recent deformation, which occurred under conditions of nearly orthogonal plate convergence, may have been essentially two-dimensional (in a vertical plane), favoring Andean uplift and growth after the end of significant Eocene to Early Miocene rotations. In comparison, Eocene-Oligocene deformation, which occurred during a period of highly oblique plate convergence, may have been essentially three-dimensional, including an important component of trench-parallel mass transfer towards the Bolivian orocline (Figure 1) [see also *Hindle et al.*, 2005]. In the southern Central

Andes, northward displacements are visible in the model. This displacement field implies trench-parallel dextral transtension along the fore-arc of Central Chile.

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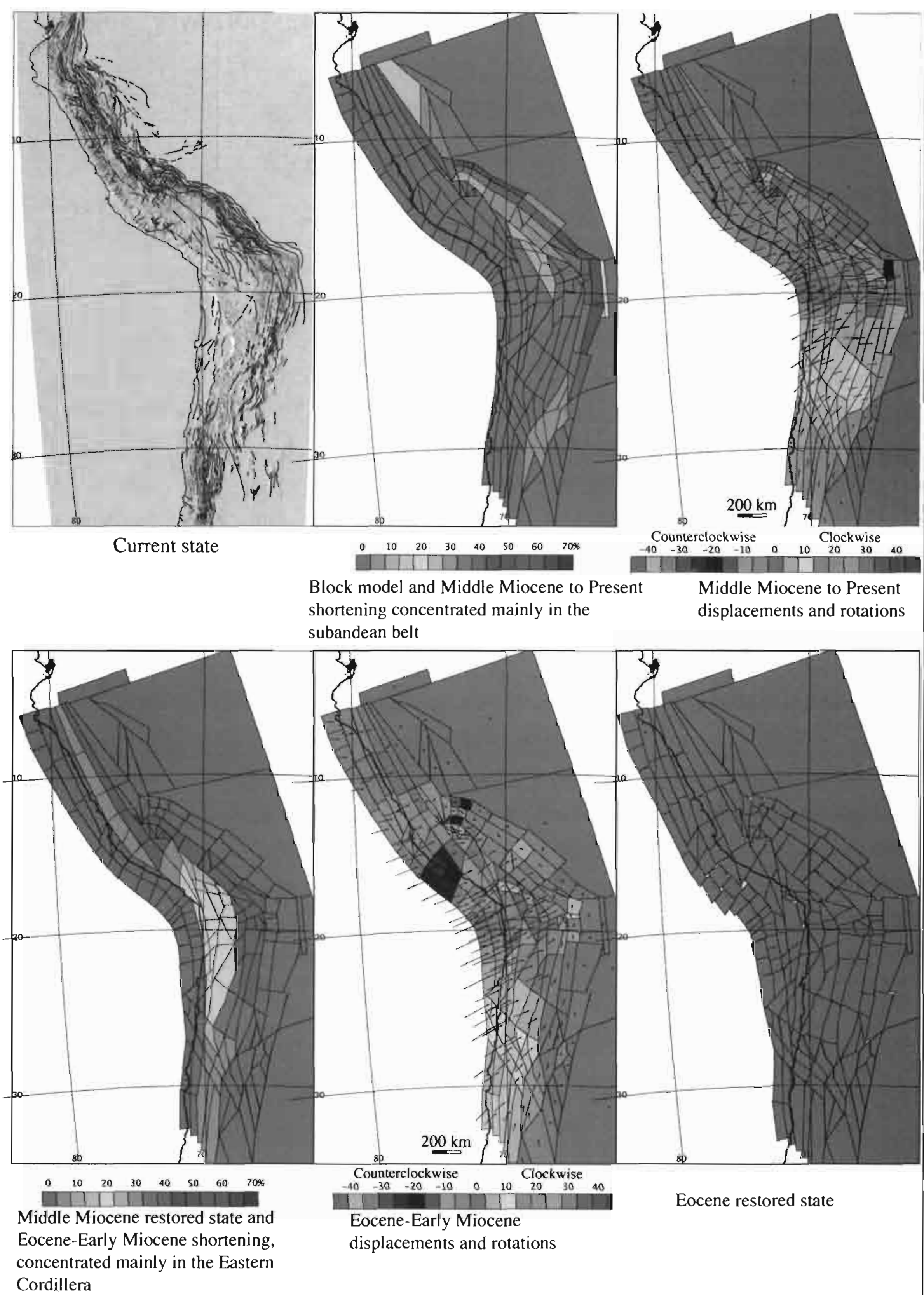

Figure 1. Plan view restoration of the Central Andes in two stages: Present to Middle Miocene (top) and Early Miocene to Eocene (bottom).