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Trench-parallel shortening in the forearc caused by subduction along a seaward-concave plate boundary: Insights from analogue modelling experiments

D. Boutelier [a,b,*], O. Oncken [c], A.R. Cruden [a]

[a] School of Geosciences, Monash University, Clayton, VIC 3800, Australia
[b] School of Environmental and Life Sciences, University of Newcastle, University Drive, Callaghan, NSW 2308, Australia
[c] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

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ABSTRACT

Three-dimensional thermo-mechanical analogue experiments are employed to test the hypothesis that oceanic subduction along a seaward-concave plate boundary can generate trench-parallel shortening in the forearc near the axis of curvature. The model deformation is analyzed with a Particle Imaging Velocimetry (PIV) system that allows for comparison of forearc deformation along the oblique limbs of the curved plate boundary and near the axis of curvature. Moreover, PIV allows for separation of the trench-parallel and trench-perpendicular components of strain, regardless of trench orientation. The resulting deformation maps show a remarkable symmetry and indicate drag of the forearc above the interplate coupling area towards the axis of curvature. Trench-perpendicular profiles show that along the oblique limbs of the plate boundary, the forearc is submitted to trench-normal shortening and trench-parallel shearing but not trench-parallel shortening or extension. This contrasts with the situation near the axis of symmetry where the forearc is submitted to trench-parallel and trench-perpendicular normal shortening, but is not sheared. The experimental results confirm that trench-normal thrusts observed in the fore-arc of the Central-Andes can be a mechanical consequence of subduction along a seaward-concave plate boundary if the degree of interplate coupling is large.

1. Introduction

Subduction zones generally display a seaward-convex curvature, which has been attributed to several processes: the sphericity of the Earth (Frank, 1968), flow in the sublithospheric mantle (Dvorkin et al., 1993; Funiciello et al., 2004; Garfunkel et al., 1986; Schellart, 2004), lateral changes of the bending strength and/or buoyancy of the subducting plate (McKenzie, 1969; Nur and Ben-Avraham, 1982), mechanical resistance on tear faults at the edges of the subducting lithosphere (Govers and Wortel, 2005; Wortel et al., 2009), or lateral changes in the strength of the magmatic arc (Boutelier and Cruden, 2013). However, several subduction zones such as the Central Andes, Japan, Solomon sea, Northern New Hebrides and Alaska display the opposite sense of curvature (seaward-concave). The kinematics of deformation generated in the forearc by subduction along a curved subduction zone is important for understanding the dynamics of subduction zones. This is because oblique convergence allows for investigation of partitioning between normal and shear stresses acting along an interplate zone, thereby constraining the general mechanics of subduction.

The kinematics of deformation associated with a seaward-concave plate boundary is particularly well illustrated in the Central Andes because it is geologically well documented and the symmetry of the Andean system allows for a relatively straightforward analysis. Convergence between the South American and Nazca plates has produced a series of tectonic provinces that generally parallel the plate boundary (Allmendinger and Jordan, 1997). However, fault scarps orthogonal to the plate boundary have been identified in the Coastal Cordillera of northern Chile (Allmendinger and González, 2010; Allmendinger et al., 2005a). These reverse faults have no significant component of oblique slip and thus accommodate horizontal shortening that roughly parallels the strike of the plate margin. Their specific location in the Coastal Cordillera near the symmetry axis of the plate boundary (Fig. 1) suggests that these anomalous faults are genetically related to the seaward-concave shape of the Bolivian orocline (Allmendinger et al., 2005a,b). However, how and why these faults formed is still uncertain and two main hypotheses have been proposed to explain them. The first hypothesis is that orogen-parallel shortening is produced during the formation of the orocline on the concave side of the buckling “beam”, represented by the Bolivian orocline. Isacks (1988) argued that along-strike variations in the magnitude of Neogene crustal shortening along the Central Andes caused the orocline and the observed pattern of predominantly counterclockwise paleomagnetic rotations of the forearc in the northern limb and clockwise rotation in the

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* Corresponding author at: School of Geosciences, Monash University, Clayton, VIC 3800, Australia. Tel.: +61 3 99024010.
E-mail address: david.boutelier@monash.edu (D. Boutelier).

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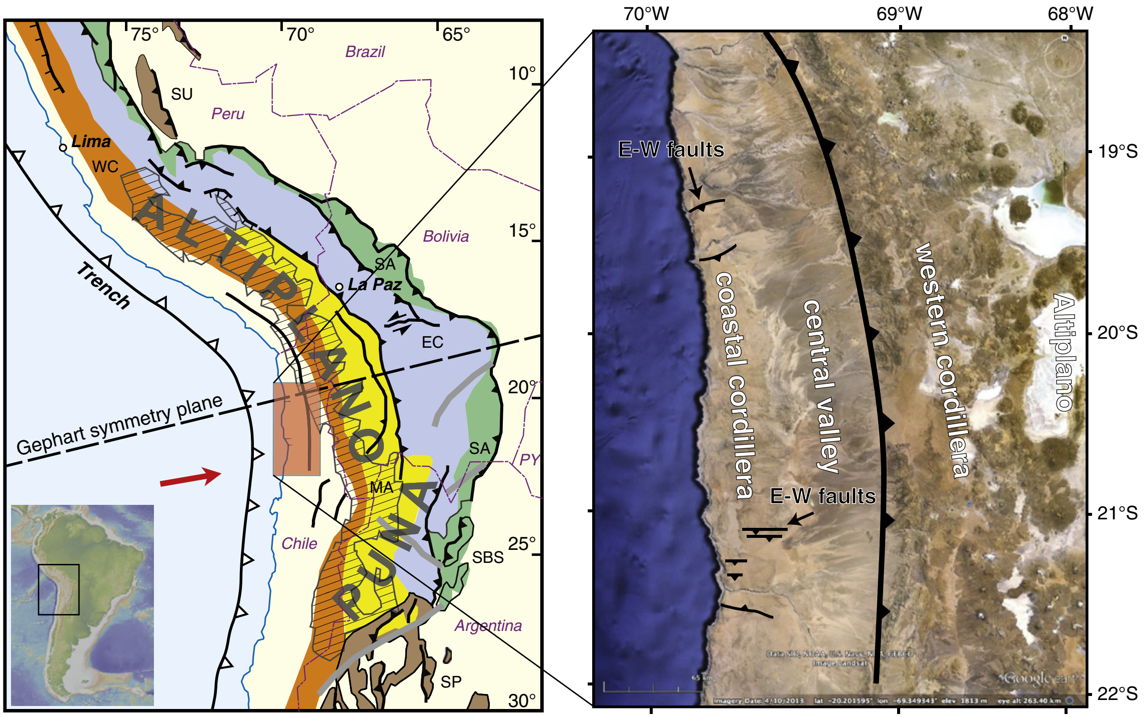

Fig. 1. Geological sketch map showing the main units of the Central Andes. WC — Western Cordillera; EC — Eastern Cordilleras; SBS — Santa Barbara System; SP — Sierras Pampeanas; SA — Subandean Ranges; MA — present magmatic arc (hatched area). Dashed line shows the present-day axis of symmetry of the orocline and subducted slab (from Gephart, 1994). The red arrow is the present day convergence vector between the Nazca and South-American plates. Satellite image (Google Earth) zoom-in on the Coastal Cordillera of the central Andes near axis of symmetry of the orocline, where trench-perpendicular thrust faults have been identified (faults redrawn after Allmendinger et al., 2005a). Inset shows location of Central Andes.

southern limb (Heki et al., 1983, 1984). However, if shortening indeed decreases away from the symmetry axis of the orocline (Oncken et al., 2006), it can only account for a fraction of the measured paleomagnetic rotations (Gotberg et al., 2009). The alternative hypothesis is that the curved shape of the plate boundary generates a deformation field with a component of shortening parallel to the boundary. Due to the map-view curvature of the trench, convergence between the Nazca and South American plates is oblique both north and south of a line of zero-obliquity that, at present, roughly coincides with the symmetry plane of the orocline and subducted slab (Gephart, 1994). Oblique convergence produces a trench-parallel shear drag on the fore arc (Chemenda et al., 2000b; Fitch, 1972; McCaffrey, 1992, 1996). For relatively high obliquity angles, convergence can be partitioned between a less-oblique slip on the plate boundary and trench-parallel displacement of a forearc sliver (Jarrard, 1986; McCaffrey, 1992, 1996). Consequently, to accommodate the resulting lateral motion of the forearc, the overriding plate margin must undergo trench-parallel extension or shortening (Ave Lallemant and Guth, 1990; McCaffrey, 1996).

This analysis presented here is complementary to modelling of a locked, curved plate boundary by Bevis et al. (2001), although they only considered interseismic elastic deformation, and not permanent long-term, visco-plastic deformation. Such long-term deformation would be better assessed using geodynamic simulations where the effects of long-term shear traction and non-hydrostatic normal stress on the plate boundary can be investigated. Using 2D numerical thin plate elastic simulations, we have previously shown that whether subduction along a seaward-concave plate boundary produces trench-parallel compression or extension near the axis of curvature depends on both the stress conditions along the interplate zone and the three-dimensional geometry of the interface (Boutelier and Oncken, 2010). Shear traction on the plate boundary, which drives trench-parallel compression near the symmetry axis, can be counter-balanced by the non-hydrostatic normal stress on the plate boundary, which tends to generate trench-parallel tension. It follows that the ratio of shear traction over non-hydrostatic normal stress, as well as the dip angle and curvature of the plate boundary, controls the stress pattern within the system.

The numerical simulations summarised above support the hypothesis that subduction along a seaward-concave plate boundary can cause long-term trench-parallel shortening near the axis of the curvature due to oblique shearing of the forearc. However, the simulations were not able to resolve the three-dimensional strain distribution in the forearc, which for computational convenience was collapsed into the edge of the 2D numerical model. It is therefore unknown where exactly trench-parallel shortening will be produced, and how trench-parallel and trench-perpendicular shortening would organize spatially in the forearc or arc domains. For example, should trench-perpendicular thrust faults be restricted to the forearc domain as observed in the central Andes (Allmendinger and González, 2010; Allmendinger et al., 2005a), or should trench-perpendicular shortening extend into the magmatic arc or beyond? Can the spatial distribution of trench-parallel shortening and its timing be employed to differentiate between the two hypothesis, thereby constraining the mechanics of the Andes, and oblique subduction in general?

In this study we quantify the spatial distribution of trench-parallel and trench-perpendicular shortening generated in the forearc by subduction along a seaward-concave plate boundary. We use numerical simulations to define the conditions that are favourable for trench-parallel shortening near the axis of the curvature, and use these results for the design of three-dimensional thermo-mechanical analogue experiments. High-resolution Particle Imaging Velocimetry (PIV) is used to measure the forearc deformation pattern precisely and its spatial variations.

2. Modelling techniques

2.1. Modelling scheme

Since we focus on the mechanical interactions between lithospheric plates along a convergent boundary, we employ a simplified kinematic