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Implications of elastic dislocation modeling on permanent deformation in the northern Chilean forearc

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Introduction

Elastic half-space dislocation models of interseismic strain accumulation in the northern Chilean subduction zone show a strain field consistent with patterns of permanent deformation. Here we present a simple model in which the seismogenic zone of the northern Chilean margin is modeled as two segments whose boundary is in the vicinity of the Mejillones Peninsula. The northern fault, representative of the northernmost Chile segment of the Andean margin, is locked between 20 and 50 km depth, while the southern segment is modeled as locked between 20 and 38 km depth. Both fault patches dip 20° and identical dislocation magnitudes are applied to each. Examination of the strain field predicted by this interseismic elastic dislocation model yields several interesting observations connecting subduction with crustal deformation in the Coastal Cordillera. Predicted principal strain axes indicate approximately east-west extension in a narrow band of longitude overlying the downdip extent of the locked plate boundary. The increase in maximum locking depth from south to north produces an eastward longitudinal shift of this extensional zone, consistent with a similar change in the trace of the Atacama Fault System (AFS), the recent motion of which is inferred to be dominantly normal. Furthermore, the principal strain axes show a clockwise rotation in the region of the eastward shift, consistent with the changing strike of the Salar del Carmen segment of the AFS. While the relationships between elastic strain and permanent deformation remain unclear, the correlation between the locations and strikes of AFS segments and the principal extension axes predicted by the elastic modeling suggests the intriguing possibility that some part of the elastic loading resulting from plate convergence is responsible for extensional faulting in the forearc.

Elastic dislocation modeling

Elastic half-space dislocation models of surface deformation [*Okada*, 1985] have been widely used to model displacement and velocity fields based on geodetic measurement. Such data lend themselves to elastic dislocation modeling, as they are interpreted to dominantly reflect signals of elastic strain accumulation and release resulting from fault processes. In the case of a subduction zone, strain accumulation is commonly simulated [*Bevis, et al.*, 2001; *Khazaradze and Klotz*, 2003; *Klotz, et al.*, 1999] using the backslip model proposed by *Savage* [1983], which requires artificial normal fault slip on the seismogenic portion of the interplate interface in order to mimic observed surface displacements. *Bevis et al.* [2001] and *Khazaradze and Klotz* [2003] interpreted differences between GPS-measured velocities and those modeled using elastic dislocations as representative of permanent strain not predicted by the purely elastic theory. In both cases, permanent deformation is inferred to take place in regions of the Andean backarc.

Results

This work addresses the possibility that permanent deformation in the forearc results from interseismic strain accumulation. This implies that patterns of permanent deformation mirror those of elastic strain. Numerous approximately north-south striking faults define the structural character of the Coastal Cordillera, and these features are particularly evident in the Antofagasta region (~22-26°S). The dominant structure of the northern Chilean forearc is the Atacama Fault System (AFS), a feature first formed during the Mesozoic [*Scheuber and Andriessen*, 1990] when the Coastal Cordillera represented the Andean arc, but presently reactivated for the most part as a high angle normal fault. Three mechanisms have been proposed to explain the recent rupture of the AFS and other extensional faults in the region: interseismic flexure, coseismic elastic strain release, and longer term processes associated with subduction erosion [*Delouis, et al.*, 1998]. Extension due to subduction erosion results from a gravitational instability due to removal of material at the trench, causing extension on the middle continental slope and possibly further inland [*von Huene and Ranero*, 2003]. *Delouis et al.* [1998] suggest that the northern Chilean forearc exists in a state of extension and that rupture of crustal faults occurs during coseismic strain release when that extension is enhanced.

Our preliminary model of interseismic loading in the Antofagasta region suggests that the pattern of interseismic strain is consistent with the distribution of normal faults. We simulate interseismic strain by applying a slip vector oriented N75E, parallel to the convergence direction [*Bevis, et al.*, 2001]. The slip vector is applied to two rectangular fault patches, both of which dip 20°E (Fig. 1). The updip extent of each fault patch is located at 20 km depth and the boundary between the two is located at approximately 23.25°S, roughly coincident with the mean latitude of the Mejillones Peninsula. The northern patch is 90 km wide, corresponding to a downdip extent of 50 km, while the southern segment is 50 km wide, extending to 38 km depth. The geometry and dimensions of the fault patches to which the slip is applied represent the locked or seismogenic portion of the plate boundary.

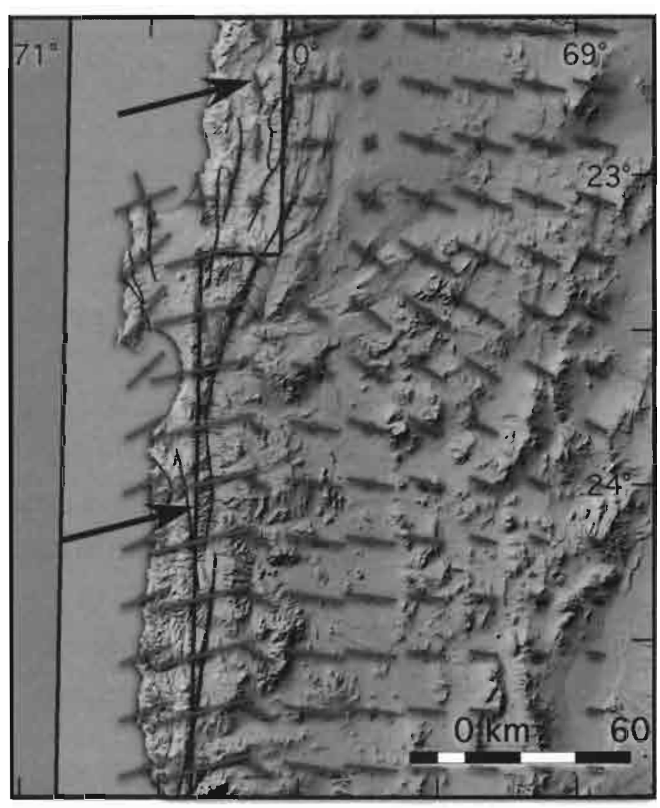

Figure 1. Principal strain axes predicted by the two segment model. Red bars show maximum principal extension; blue bars show minimum. Surface projection of fault is outlined in black and arrows denote slip vector. Barbed black lines indicate prominent normal fault scarps.

The surface displacement field predicted by the models is used to calculate the displacement gradient from which we extract the principal strain axes. Principal extension axes calculated in 20 km intervals are oriented approximately parallel to the applied slip vector away from the boundary between the two fault segments, but are deflected near this contact. Extension in the direction of plate convergence is concentrated in a narrow longitudinal range (~0.25-0.5° wide) overlying the downdip limit of the locked plate boundary. Because the northern fault segment is wider and deeper, its downdip extent is located further east than that of the southern patch. This change in position of the extensional field is consistent with the change in trace of the AFS, which strikes approximately N-S north of ~23°S and south of 23.75°S (Fig. 1). The NE strike between these fault segments is also predicted by the elastic model (Fig. 1). Additional examples of correlation between the elastic model and the extent of normal faulting exist on and immediately northeast of the Mejillones Peninsula. Clockwise rotation of axes of maximum principal extension from the south end of the peninsula to the north is consistent with the change in fault strike from NW to N. East of the north end of the peninsula, normal faulting becomes less evident as predicted extensions decrease in magnitude northward.

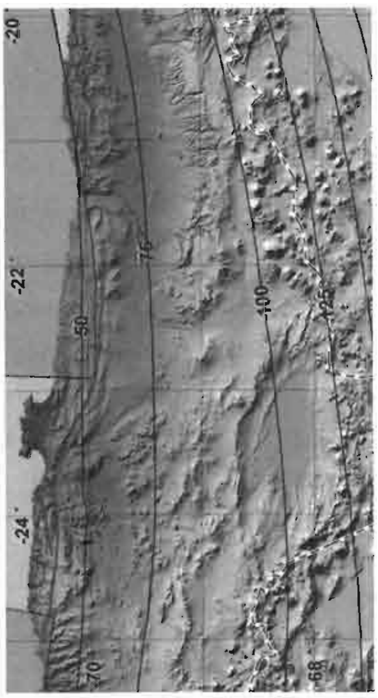

Figure 2. Topography of the Coastal Cordillera with prominent fault scarps (red), contours to Wadati-Benioff zone (black), and preferred seismogenic zone of Khazaradze and Klotz (2003, gray shading).

Spatial and temporal implications

The similarities observed between principal strain axes predicted by elastic dislocation modeling and normal faulting in the Antofagasta region suggest that forearc structures are intimately tied to the subduction process, particularly the accumulation of interseismic strain. The strain map we have presented (Fig. 1) is unique to the two-segment model for the subduction thrust in the Antofagasta region; models employing a single, through-going fault with uniform maximum locking depth along strike do not exhibit the traits of the two-segment simulation. Along strike variations in the inferred maximum depth of the seismogenic zone are consistent with concentrations of faults (Fig. 2). North of Antofagasta around 20.5°S, the 50 km Wadati-Benioff zone contour line [*Cahill and Isacks*, 1992] trends offshore, consistent with a change in strike of faults. South of Antofagasta, normal faults also project offshore following the trend of the downdip extent of the locked plate boundary preferred by *Khazaradze and Klotz* [2003] in their modeling of GPS data (Fig. 2). Therefore, it seems that the interpreted downdip extent of the seismogenic zone and associated field of extensional strain are consistent with fault patterns for much of the northern Chilean forearc.

The maximum depth of interplate coupling has been addressed by several studies in northern Chile [*Delouis, et al.*, 1996; *Khazaradze and Klotz*, 2003; *Tichelaar and Ruff*, 1991]. *Tichelaar and Ruff* [1991] use seismic waveform inversion to deduce that the maximum coupling depth is at least 45-48 km for northern Chile (18°-24°S) and no deeper than 36-41 km for the Taltal region (24°-27°S). Thus, it seems plausible that a southward shallowing transition in coupling extent exists around Antofagasta. In their local seismic study of the Antofagasta region, *Delouis et al.* [1996] note a reduced number of earthquakes occurring between 35 and 50 km depth and indicate that these events are more consistent with reverse faulting than underthrusting. *Khazaradze and Klotz* [2003] show a change in extent of seismogenic zone from 50 km to 35 km depth around the latitude of the Mejillones Peninsula based on elastic modeling of GPS data. These data, however, are complicated in the region of the transition by post-seismic deformation associated with the 1995 Antofagasta earthquake. In contrast to these results, *Comte et al.* [1994] suggest that the maximum depth of the coupled interplate zone is 47 km based on locations of thrust-type earthquakes or 70 km based on the transition from compressional to tensional events. An alternative to our model of varying locking depth is a simulation invoking a transitional zone of locking within the lower part of the seismogenic zone, similar to that proposed by *Chlieh et al.* [2004]. Such a model would also require a change in subduction behavior around the Mejillones Peninsula in order to mirror the pattern of extensional faulting, but the extent of the seismogenic zone defined by this model may better agree with that proposed by *Comte et al.* [1994].

If the modern interseismic strain field indeed dictates the evolution of normal faults in the Coastal Cordillera, several temporal considerations need be made. First, because many neotectonic structures are inferred to be reactivated Mesozoic arc features, the original structures may have formed with strikes similar to those observed today. Alternatively, if the Coastal Cordillera were pervasively fractured between the time of its formation and initiation of the neotectonic fault activity, interseismic loading may have formed the recent faults in accordance with its strain field. Second, the difference in coupling depth incorporated into our elastic model suggests that the Mejillones Peninsula may be linked to a significant change in subduction behavior. Analyses of earthquakes [e.g. *Delouis, et al.*, 1997] and bathymetry data [*von Huene and Ranero*, 2003] along the Chilean margin suggest that the peninsula represents the surficial expression of a subduction fault segment boundary, acting as a barrier to earthquake rupture. Third, the longitudinal position of the seismogenic zone must not have changed drastically in the past several million years, resulting in the relatively narrow zone of observed normal faulting. The rate of subduction erosion estimated by *von Huene and Ranero* [2003] suggests a westward shift of the zone of interseismic extension, but the magnitude of shift is consistent with the distribution of faults observed today.

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