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Surface cracks record long-term seismic segmentation of the Andean margin

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ABSTRACT

Understanding the long-term patterns of great earthquake rupture along a subduction zone provides a framework for assessing modern seismic hazard. However, evidence that can be used to infer the size and location of past earthquakes is typically erased by erosion after a few thousand years. Meter-scale cracks that cut the surface of coastal areas in northern Chile and southern Peru preserve a record of earthquakes spanning several hundred thousand years owing to the hyperarid climate of the region. These cracks have been observed to form during and/or shortly after strong subduction earthquakes, are preserved for long time periods throughout the Atacama Desert, demonstrate evidence for multiple episodes of reactivation, and show changes in orientation over spatial scales similar to the size of earthquake segments. Our observations and models show that crack orientations are consistent with dynamic and static stress fields generated by recent earthquakes. While localized structural and topographic processes influence some cracks, the strong preferred orientation over large regions indicates that cracks are primarily formed by plate boundary–scale stresses, namely repeated earthquakes. We invert the crack-based strain data for slip along the well-known Iquique seismic gap segment of the margin and find consistency with gravity anomaly–based inferences of long-term earthquake slip patterns, as well as the magnitude and location of the November 2007 Tocopilla earthquake. We suggest that the meter-scale cracks can be used to map characteristic earthquake rupture segments that persist over many seismic cycles, which encourages future study of cracks and other small-scale structures to better constrain the persistence of asperities in other arid, tectonically active regions.

INTRODUCTION

The characteristic earthquake model of seismic recurrence suggests that a given fault segment ruptures repeatedly in earthquakes of similar magnitude and areal extent (Schwartz and Coppersmith, 1984). While some historical (Comte and Pardo, 1991) and paleoseismic (Sieh, 1996) records support this model, it is unclear whether these seismic segments are truly long-lived, because geologic indicators of distinct earthquakes usually persist for only a few thousand years (up to ~10 events). To assess the longevity of the segmented nature of seismicity, we require data that reflect deformation caused by hundreds to thousands of repeated earthquakes.

Arrays of meter-scale surface cracks that penetrate coastal regions of the northern Chile and southern Peru forearc provide insight into the long-term nature of great earthquakes (magnitude 8 and larger) along the plate boundary. We use 2.5-m-resolution satellite imagery available in Google Earth to map concentrations of cracks throughout the Andean forearc between 17.5°S and 23.5°S (Fig. 1); examination of regions outside these latitudinal bounds yields only sparse examples of cracking, likely due to slightly wetter climatic conditions (Ewing et al., 2006) and presence of unconsolidated sediment (Rech et al., 2003), both of which inhibit crack preservation. We complement the remote sensing with field observations at several localities (Loveless, 2008; Loveless et al., 2005) and, because cracks throughout the study area are morphologically similar, we generalize our field results to regions we have not visited. In general, crack clusters show preferred orientations that vary on spatial scales similar to great earthquake rupture areas. Between 19°S and 23°S, the estimated latitudinal bounds of the great 1877 Iquique earthquake (Comte and Pardo, 1991), mean length-weighted crack strike rotates from NW to N-NE. At several localities, including east of the Mejillones Peninsula (23°S), there are populations of cracks showing a bimodal distribution in strike, with one set striking NE and the other NW (Fig. 1). Cracks near Ilo, Peru, strike at a high angle to the coastline and plate boundary, approximately parallel to the direction of plate convergence.

Hyperaridity in the region, which has persisted for at least the past 6 m.y. (Hartley and Chong, 2002), if not since before 16–18 Ma (Dunai et al., 2005; Rech et al., 2006), allows for long-term preservation of the cracks. The gypsum-indurated soil that covers much of the coastal region between elevations of 300 and 1200 m (Rech et al., 2003) provides a durable surface crust that further enhances crack preservation. Our field observations reveal crack apertures ranging from tens of centimeters to >1 m; these cracks can be mapped using the imagery, but we cannot comprehensively define their apertures. Although many cracks are preserved in the gypsum-indurated crust (Fig. 1, inset), there are numerous fissures penetrating as much as 12 m into bedrock. We interpret the numerous layers of gypsum plated vertically onto crack walls as an indication of repeated episodes of sealing and reopening. The rate of gypsum accumulation is unknown, limiting the information that it can provide about the age of cracks. However, based on cosmogenic dating of the geomorphic surfaces into which the cracks cut and morphologically similar neotectonic structures (González et al., 2006), we propose that the cracks represent deformation as old as several hundred thousand years, encompassing thousands of ~100 yr interplate earthquake cycles (Loveless et al., 2005).

Local structural, topographic, and/or geomorphic effects and stresses related to earthquakes within the subducting slab (Marquardt et al., 2006) influence the formation of some cracks. In particular, some cracks strike parallel to crustal faults (González et al., 2008) and drainages (Keefer and Moseley, 2004), indicating that preexisting linear features can affect crack strike. However, the large-scale patterns of strike change (Fig. 1) and the fact that cracks were generated by the 1995 M_w 8.1 Antofagasta, Chile (González and Carrizo, 2003), and 2001 M_w 8.5 Arequipa, Peru, events (Keefer and Moseley, 2004) indicate that interplate earthquakes are the principal driver of formation. Mode 1 cracks, which, based on the paucity of observed lateral offset, we infer most cracks to be (Loveless et al., 2005), open in the direction of least compressional principal stress (σ_3) and therefore strike parallel to the most compressional direction (σ_1) (Pollard and Segall, 1987). By constructing a regional map of crack strikes, we effectively map the orientations of the principal stress axes responsible for their formation. The stress field produced by a subduction zone earthquake varies as a function of the slip distribution on the fault, with σ_1 axes varying from nearly parallel to the fault slip vector around the center of the rupture zone to oblique to the slip direction near the rupture terminations (Fig. 2).

MODELING COSEISMIC STRESS FIELDS

In order to explore the relationships between the mode 1 surface cracks and plate boundary earthquakes, we calculate the coseismic

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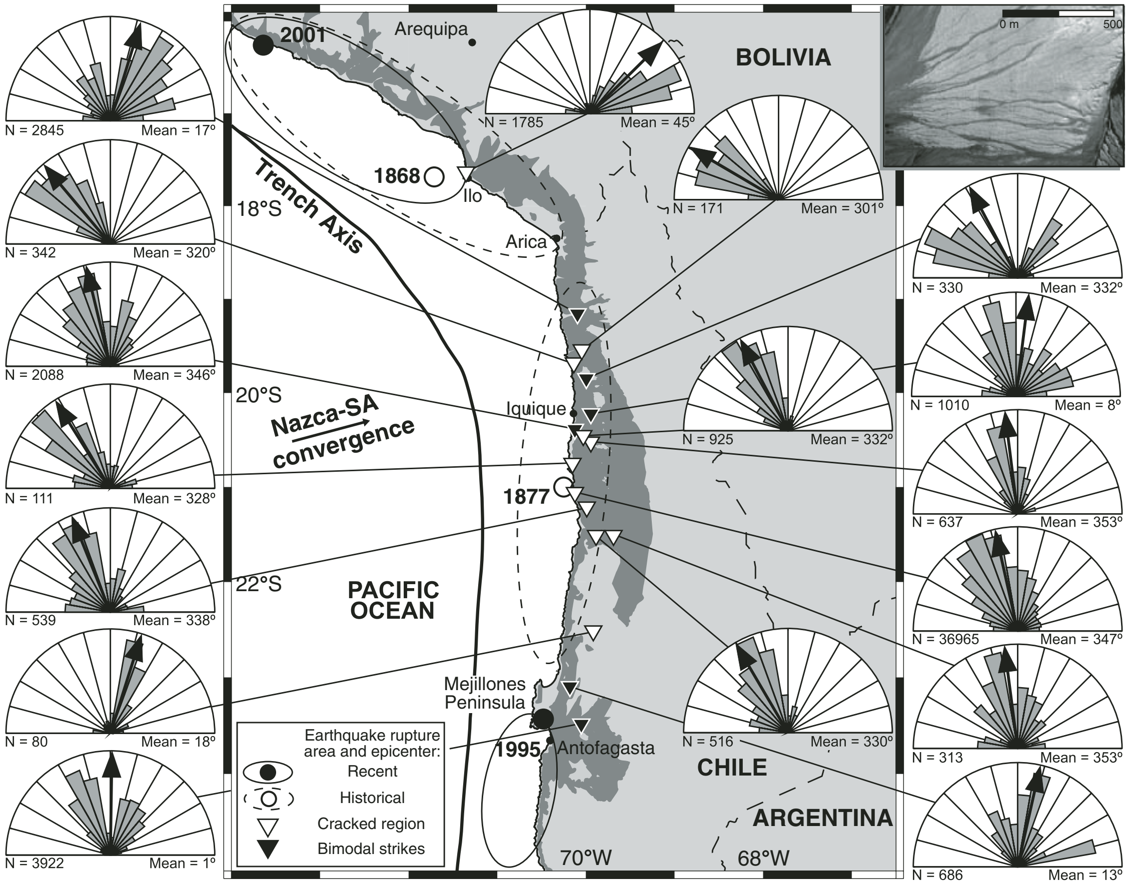


Figure 1. Map of northern Chile and southern Peru forearc regions. Ovals indicate approximate rupture areas of most recent earthquakes on four segments of the plate boundary; large dots represent inferred epicenters. Rose diagrams show length-weighted distribution of crack strikes; black vectors denote the mean strikes. Inverted triangles show the position of the population; filled symbols denote bimodal distribution in strike (see the Data Repository [see footnote 1]). Dark gray region onshore shows area between 300 m and 1200 m elevation, delineating the bounds within which gypsum precipitates from dense coastal fog (Rech et al., 2003). Inset IKONOS satellite image in upper right corner shows example of surface cracking. Cracks are concentrated in gypsum-indurated sediment and are identified as parallel, N-S–striking dark lines in light-colored sediment. Darker regions are unconsolidated sediments in which cracks are not well preserved. SA—South America.

principal deviatoric stress fields related to great earthquakes on four segments of the Andean margin: the 2001 Arequipa, 1868 M ~8.5 southern Peru, 1877 M ~8.5 Iquique, Chile, and 1995 Antofagasta events (rupture areas shown in Fig. 1; for a detailed discussion, see the GSA Data Repository[1]). We use published solutions for slip distributions of the 1995 (Pritchard et al., 2006) and 2001 (Pritchard et al., 2007) events and approximations of the historical earthquake slip patterns (Comte and Pardo, 1991). Figures DR1–DR4 illustrate the relationships between the forward models of coseismic static stress fields and the permanent strain demonstrated by the surface cracks.

In general, there is good agreement between the observed mean strikes of cracks and the orientation of modeled σ_1 axes. In the case of the bimodal strike crack populations east of the Mejillones Peninsula, we find that the NW-striking cracks are consistent with the NE-SW–directed σ_3 axes induced by events on the Antofagasta segment (Fig. DR1), while the NE-striking cracks are opened by the NW-SE–trending σ_3 axes related to seismicity on the Iquique segment (Fig. DR2). Similarly, the bimodal crack clusters in northernmost Chile are affected by stress related to earthquakes on the Iquique and southern Peru segments of the margin (Figs. DR2 and DR3).

The rotation of mean crack strike from N-NE to NW from south to north along the length of the Iquique segment (Fig. 1) agrees with the stress field predicted by the forward models (Figs. 2 and DR2). The cracks mapped near the city of Ilo, Peru, are near the center of the estimated rupture zone of the 1868 earthquake and strike nearly perpendicular to the σ_1 orientation predicted by the 1868 model, indicating that these cracks are minimally affected by the static stress caused by earthquakes on this segment, on which the great 1604 earthquake also occurred (Comte and Pardo, 1991). The mapped cracks are suggested to have formed either during or shortly after the 2001 Arequipa earthquake (Keefer and Moseley, 2004). En echelon map patterns of these cracks suggest accommodation of W-SW–directed left-lateral shear in addition to opening, consistent with the kinematics reported for nearby faults (Audin et al., 2008). This indicates that the cracks near Ilo are mixed mode (1 and 2), and thus we expect that σ_1 for the stress field that created them should be oblique to the crack strike, as predicted by our model of the 2001 event (Fig. DR4).

INVERTING CRACK DATA FOR PALEOSEISMIC SLIP

Studies of historical seismicity have relied on qualitative written records of sustained damage (Comte and Pardo, 1991) to estimate event magnitude and location. Given the agreement between predicted stress fields and observed crack strikes, we propose that cracks can provide quantitative constraints on the slip distribution of paleo-earthquakes. Because the inferred rupture limit of the 1877 earthquake encompasses 16 of the 17 cracked regions, we use the cracks to invert for plausible slip distributions related to that event, or a sum of events occurring on the segment. In doing so, we make the assumption that cracks used to constrain the slip pattern open exclusively due to coseismic stress earthquakes on this segment, plus a contribution from regional stress (see the Data Repository).

The mean residual angle between the observed crack strikes and those predicted by our preferred inversion is 8.2° (Fig. 3). While the solution for coseismic slip is nonunique (see the Data Repository), several robust features are

[1]GSA Data Repository item 2009006, supplementary text (describing bimodal statistics, and forward and inverse modeling parameters), Figures DR1–DR7 (results of static and dynamic earthquake models), and Tables DR1–DR3 (crack population statistics, earthquake parameters, and inverse model permutations), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

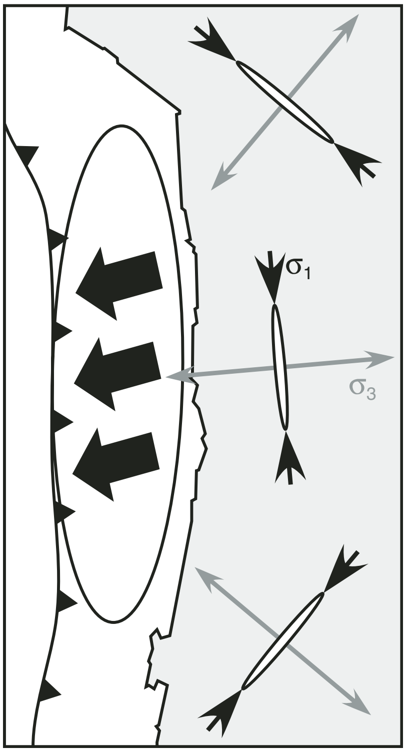
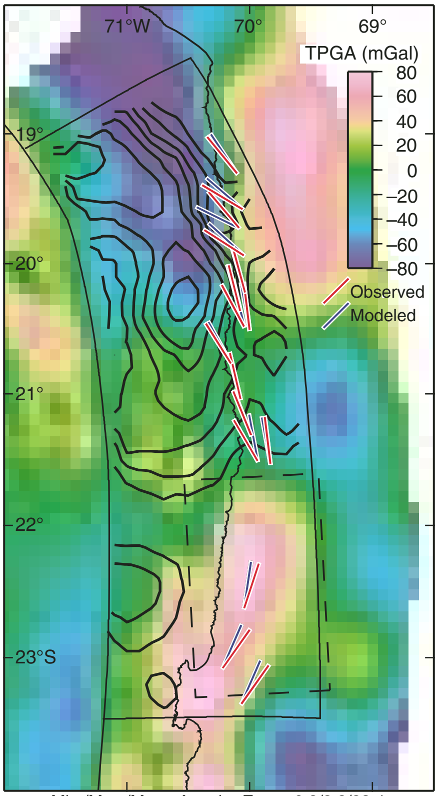


Figure 2. Schematic relationship between subduction zone earthquake rupture area (offshore ellipse with bold arrows denoting coseismic slip vector) and principal stress exerted at surface. Gray arrows show σ_3 axes, which are approximately parallel to slip vector near center of rupture segment, opening cracks (narrow white ovals) that strike in perpendicular direction, parallel to σ_1 direction (black axes). Near rupture terminations, cracks strike oblique to earthquake slip vector.



Min./Max./Mean Angular Error: 0.8/8.2/23.4
Total Angular Error: 131

Figure 3. Preferred inverse model of the 1877 Iquique earthquake, shown as 1 m interval contour lines of coseismic slip. Slip distribution was calculated by inverting (Maerten et al., 2005) strain field represented by populations of surface cracks for slip on the subduction interface. Mean crack strike at each mapped locality is shown by red bar, and calculated σ_1 orientation at same location is indicated by blue bar; mean residual angle between observed and predicted crack strike is 8.2°. Contours are overlain on trench-parallel gravity anomaly (TPGA) constructed for Iquique segment. Region of greatest resolved slip for Iquique event coincides with strongly negative TPGA, consistent with recent studies (Llenos and McGuire, 2007; Song and Simons, 2003; Wells et al., 2003). Approximate rupture area of November 2002 M_w 7.7 Tocopilla earthquake is shown as dashed rectangle, based on information from the U.S. Geological Survey.

notable. The greatest resolved slip is concentrated ~35 km deep offshore Iquique (20.25°S), consistent with the depth of maximum slip during the 1995 earthquake and ~1° north of the epicenter of the 1877 earthquake inferred from historical data (Comte and Pardo, 1991). Smaller loci of moment release are located near 22.5°S and 23.5°S. The distance between slip patches suggests that they may represent separate earthquakes or widely spaced asperities that rupture during a single event. Because of the lack of temporal information contained in the data set, the crack-based strain field cannot distinguish a single earthquake with a heterogeneous slip distribution from several smaller events. Based on aftershocks mapped by the U.S. Geological Survey, the November 2007 M_w 7.7 Tocopilla earthquake ruptured the margin between ~22°S and 23°S (Fig. 3), indicating that it broke a portion of the plate boundary on which little Iquique event slip is predicted by the inversion. This suggests that much of the segment ruptures during truly great earthquakes such as that of 1877, but the portions remaining unbroken slip in smaller events.

DISCUSSION

Recent studies (Llenos and McGuire, 2007; Song and Simons, 2003; Wells et al., 2003) have found a correlation between negative forearc trench-parallel gravity anomalies and zones of large-magnitude slip during strong subduction zone earthquakes. We construct a trench-parallel gravity anomaly (Sandwell and Smith, 1997; Song and Simons, 2003) field for the Iquique segment to compare with the slip distribution resolved from our inversion of the crack-based strain data (Fig. 3). The region in which resolved slip is greatest coincides with an area of strongly negative trench-parallel gravity anomalies. The lack of resolved slip at shallow depths south of 21°S and occurrence of the smaller Tocopilla earthquake near 22°S are consistent with the prevalence of positive trench-parallel gravity anomalies, which predict slip of lower magnitude during the characteristic Iquique event. The forearc gravity field is not a transient property, thus both the gravity field and our inversion of geological data place constraints on long-term patterns of great earthquake slip.

In addition to the static stresses, dynamic stresses associated with the passage of seismic waves can cause cracking of the surface (Dalguer et al., 2003). We calculate the temporal evolution of stress induced at the surface by the 1995 and 2001 earthquakes and find that stress axes calculated from static dislocation models are reasonably similar in orientation to the dynamic principal stresses (Fig. DR7). This indicates that our regional-scale mapping of cracks places constraints on the extent and distribution of slip associated with plate boundary earthquakes, regardless of whether static or dynamic stress is the primary driver of crack evolution. The method used to calculate dynamic stress (Cotton and Coutant, 1997) does not take into account changes in material properties such as the presence of existing faults and lithologic heterogeneity that may localize deformation. We suggest that dynamic stressing is responsible for the formation of the cracks near Antofagasta, which formed in poorly consolidated sediments parallel to a nearby NE-striking fault scarp during the 1995 event (González and Carrizo, 2003) and may have been affected by the soil characteristics and fault structure.

We suggest that great earthquakes along the northern Chile and southern Peru margin repeatedly rupture areas several hundred kilometers in length in quasi-characteristic earthquakes. If the location of segment boundaries varied substantially on hundred thousand year time scales, we would expect cracks to show a range of strikes rather than one or two preferred orientations, or a greater frequency of lateral offset. Historic records show that not all segments completely rerupture in single earthquakes but may sometimes break in several smaller events (Kanamori and McNally, 1982). However, our models of earthquake slip and crack formation indicate that on a regional scale, the stress field is more sensitive to the extent of slip than details of its distribution (Fig. DR6). This suggests that earthquakes on a given segment of the plate boundary may vary in their slip distribution, but the accumulated strain exhibited by surface cracks implies that the dimensions and boundaries of characteristic earthquake rupture remain relatively constant.

The existence of long-lived earthquake segments has several implications. Knowledge of segment dimensions and boundary locations is important for determining earthquake recurrence intervals and thus assessing seismic hazard. Numerous explanations for the segmented nature of subduction zone earthquakes have been proposed, including topographic features on the slab, interaction with upper plate faults (Audin et al., 2008), and changes in upper plate structure, and our suggestion that segments are long-lived and can be mapped by surface features will provide important constraints on these hypotheses. Finally, surface cracks have been observed to form coseismically in numerous tectonic settings, including along strike-slip faults on the Tibetan Plateau (Bhat et al., 2007) and in the Middle East (Fielding et al., 2005), and our work motivates large-scale mapping of these features using high-resolution global imagery, such as that available from Google Earth, to determine whether long-lived seismic segmentation exists in these and other areas.

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