Permanent Forearc Extension and Seismic Segmentation: Insights from the 2010 Maule Earthquake, Chile

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Abstract. Geologists have long known that Neogene normal faults are the major structural element of the Andean Coastal Cordillera, but their relationship to the subduction seismic cycle was unclear until the 2010 Mw 8.8 Maule earthquake in central Chile. Some of the largest aftershocks occurred on upper plate normal faults, including the Mw 6.9 and 7.0 events of the Pichilemu sequence. Using published coseismic GPS displacements and slip distribution models we compute the static strain and stress fields imposed on the forearc by the megathrust. The normal Coulomb stress increment (CSI) on the Pichilemu fault has maximum positive stresses as high as 4.0 MPa. Regionally, the megathrust produced a semi-elliptical, radial pattern of static extension and tension (CSI>1.5 MPa) along the Coastal Cordillera enclosing the rupture area. This elliptical pattern mimics the trends of the major mapped faults. The deformation field produced by a great subduction earthquake is an effective mechanism to generate permanent extension above the rupture, reactivating suitably-oriented, long-lived normal faults. We suggest that the semi-elliptical outline of the first-order structures along the Coastal Cordillera may define the location of a characteristic, long-lived megathrust segment. This implies a persistence over the Neogene of great subduction ruptures along the Maule earthquake region.

Keywords: Subduction earthquakes, Upper plate normal faulting, Seismic cycle, Seismic segmentation.

1 Introduction

On February 27, 2010, approximately 600 km of the Nazca-South America plate boundary ruptured to generate the Mw 8.8 Maule earthquake on the subduction megathrust in central Chile (Figure 1). Curiously, the two largest “aftershocks” were intraplate normal fault earthquakes with magnitudes of Mw 7.4 and Mw 7.0, one in the outer rise of the down-going oceanic slab and the other within the upper plate forearc directly above the rupture area (Pichilemu fault; Farías et al., 2011). A close examination of the geology along the Chilean forearc, especially that part which overlaps the zone of interplate seismogenic coupling, shows that Neogene normal faults are one of the most common structural elements, far outnumbering reverse faults (e.g., Allmendinger and González, 2010). How do upper plate normal faults relate to interplate boundary thrusting, and are there specific conditions that favor formation of normal faults?

Figure 1. Shaded relief of the Maule earthquake region on central Chile, enclosed by the black ellipse. The circles show the location of intraplate normal aftershocks from February 27, 2010, to October 10, 2010, reported by the Global CMT catalog. The aftershocks size is scaled by moment magnitude. The red lines over the continent correspond to upper-crustal faults from the 1-million Chilean geological map (SERNAGEOMIN, 2003). The box depicts the Pichilemu sequence area. Digital elevation model based on ETOPO2 NOAA.

We combine geophysical and geological data with principles of linear elasticity, dislocation theory and Coulomb rock fracture criteria to explore how permanent upper plate deformation relates to release of elastic strain energy during great earthquakes. Modeling the infinitesimal static strain and stress fields imposed in the upper plate by the interplate megathrust, we provide a mechanical explanation for continental Mw 7.0 intraplate normal faulting triggered by the Maule earthquake. Finally, we compare the coseismic and interseismic crustal deformation signals and discuss both the contribution of
subduction earthquakes to generate long-term extensional provinces along convergent margins, and how this structural grain of the forearc provides an insight for a long-lived seismic segmentation, or seismic gap, theory.

2 Methods and Results

2.1 CSI on the Pichilemu Normal Fault

Here, we use the slip distribution models for the Maule earthquake to produce coseismic forward models of the static Coulomb stress increment (hereafter CSI), or Coulomb stress change, resolved on the Pichilemu receiver normal fault. By varying the slip distribution model inputs of the Maule earthquake we obtained positive CSI averaged across the Pichilemu normal fault that range from 0.4 to 2.3 MPa. Maximum CSI estimations reached values as high as 4.0 MPa.

Figure 2. Coseismic CSI resolved on the Pichilemu normal receiver fault. The results from the input slip distribution by Lorito et al. (2011) is shown here as a representative example. The inset shows the horizontal projection of the fault (N36°W, 55°SW). Positive stress values (red colors) mean faulting enhancement in a -90° rake direction (normal). The stereonet shows in blue the nodal plane of the largest aftershock used to determine the fault geometry (from GCMT catalog).

2.2 Regional Coseismic CSI

To extend these results to the entire forearc, we calculate the CSI and strike of the “optimally oriented” normal faults over horizontal grids at different depths, covering the entire forearc above the Maule rupture area. The optimal orientation is defined by the maximum value of CSI modeled at each grid element, which is also shown in our results as color contoured maps, along a normal slip vector with rake = −90°. The model-generated normal faults delineate a semi-elliptical pattern enclosing the rupture area and zones of maximum slip (Figure 3). The entire outer forearc wedge has positive CSI values (>1.5 MPa). More importantly, the modeled strikes fit the orientation of the upper crustal structures.

Figure 3. Coseismic regional CSI over the continent resolved on “optimally-oriented” modeled normal faults (rake -90°, dip 60°), calculated at 10 km depth, above the Maule subduction segment (result from slip model by Lorito et al., 2011). The black lines represent the strike of the modeled faults at each element of the horizontal grid. Note the agreement in orientation between the modeled faults and the mapped crustal structures (green lines). Positive CSI values (red colors) mean that normal faulting is enhanced. The magnitude of each square of the grid is determined by the stress resolved on the modeled fault which optimal orientation determines the highest possible value of CSI at the specific location of the element. The maximum values of positive stress are concentrated along the outer forearc.

2.3 Regional Interseismic CSI

We calculate the interseismic CSI over the forearc on “optimally oriented” normal faults using a semi-2D gaussian synthetic approximation for coupling and backslip. Here we present a computation for a 100-year interseismic period. The down-dip backslip was calculated using the convergence vector projected onto an 18° dip subduction interface, which variable strike mimics the trend of the trench (Figure 4). The interseismic deformation field suppresses normal faulting in the upper crust wedge (negative CSI). For most of the Coastal Cordillera the optimal modeled orientation disagrees with the structural grain (Figure 4).

3 Discussion and Conclusions

The static coseismic deformation field, imposed in the upper plate by a great subduction earthquake, is an
effective mechanism for generating convergence-parallel, permanent extension above the seismogenic zone. This extensional field is consistent with the large upper plate normal aftershocks generated by the Maule earthquake and probably the normal aftershocks that followed the Tōhoku earthquake, as well. The long-lived normal faults in the outer forearc wedge are likely reactivated whenever the slip on subduction megathrust segments is appropriately oriented to provide the proper loading conditions.

The semi-elliptically oriented coseismic stress field generated by slip on the megathrust mimics the semi-elliptical outline of the first-order normal faults along the Coastal Cordillera. The interseismic deformation field produces convergence-parallel shortening and enhanced minor reverse faulting in the upper crust, which agrees with geological observations (Aron et al., this congress). Because upper plate normal faulting is suppressed during the interseismic period, discrete events like subduction earthquakes probably play a major role in the genesis of permanent extensional provinces along the leading edge of non-collisional convergent margins (Figure 5).

Such architectural pattern may be persistent over the geologic time in the region overlying the Maule rupture zone, at least throughout the Neogene (Aron et al., this congress). We suggest that the semi-elliptical outline of the first-order structures along the Coastal Cordillera may indicate cyclic accumulation of slip on relatively constant, long-lived seismic segments (Figure 5a). Great events along the Maule segment appear to have been ruptured repeatedly over time, thus enhancing the morphological and structural expression of appropriately-oriented forearc structures.

Figure 4. Interseismic regional CSI on “optimally-oriented” normal faults at 10 km depth above the Maule subduction segment, over a 100-year period. The inset shows the semi-2D gaussian function for interseismic coupling. For this case the CSI resolved on optimally-oriented structures over the upper plate suppressed normal faulting. Most of the forearc is affected by a negative field (blue) and the modeled faults do not match the crustal structures.

Figure 5. Conceptual model of possible behavior of subduction earthquakes and the associated result in the structural grain. (a) Long-lived segments produce a semi-elliptical geometry of large normal faults resulting from the average slip, cyclically accumulated over time. The bimodal orientations represent segment boundaries. (b) Random distribution of oblique and trench-parallel structures result from coseismic deformation imposed by segments that change location over time. The ellipses represent the hypothetical pattern of the finite slip distribution on the megathrust (darker colors are higher slip) and the white arrows (a) indicate the long-term extensional axis. Tr, Cl and CC stands for trench, coastline and Coastal Cordillera respectively.

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