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

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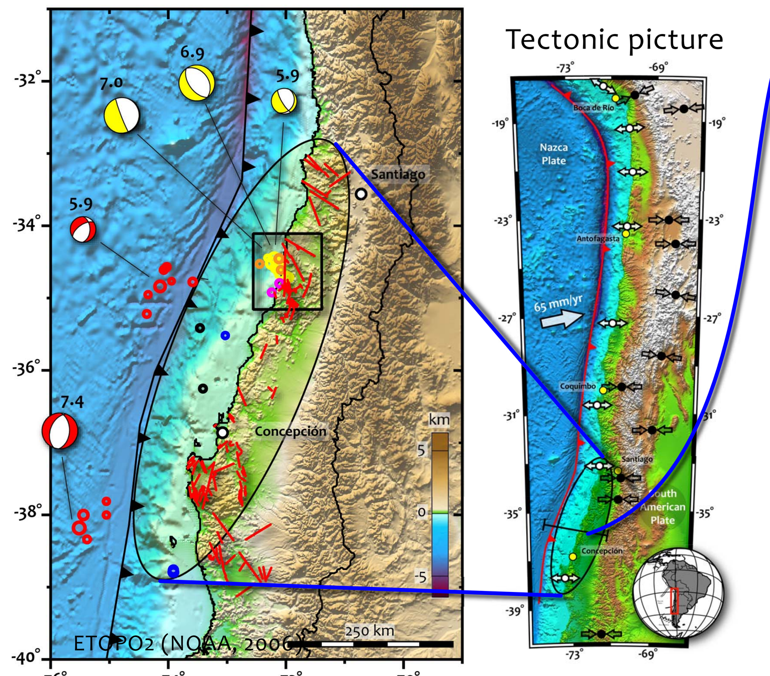
INTRODUCTION

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 south-central Chile (Figures 1 and 2). 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 basement rocks of the forearc, the Pichilemu sequence** (Farías et al., 2011). A close examination of the length of the Chilean forearc, especially that part which overlies the zone of subduction interseismic coupling, shows that **Neogene normal faults are one of the most common structural elements, far outnumbering reverse faults** (e.g., Allmendinger and González, 2010).

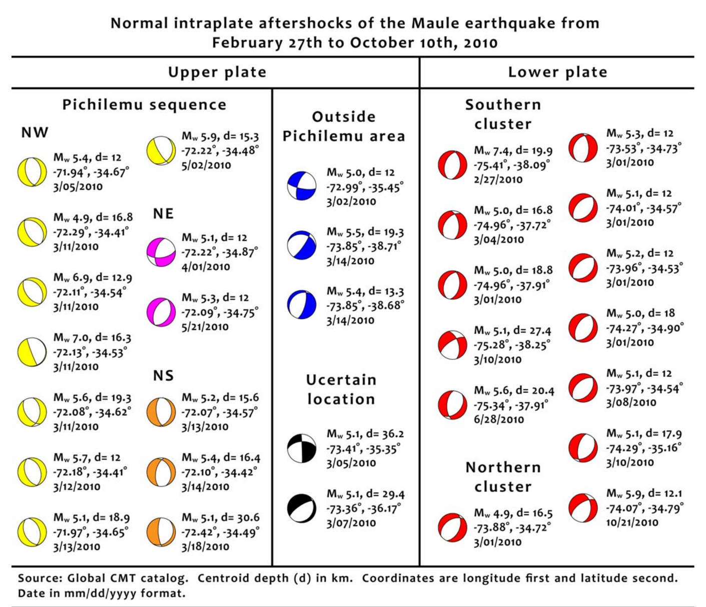
How do upper plate normal faults relate to plate boundary thrusting and are there specific conditions that favor production of normal faults?

In this work, we combine geophysical and geological data with principles of linear elasticity, dislocation theory and Coulomb rock fracture criteria to explore the permanent geological deformation that accompanies the liberation of elastic strain energy during great earthquakes. Modeling the infinitesimal static strain and stress fields imposed in the upper plate by the 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.

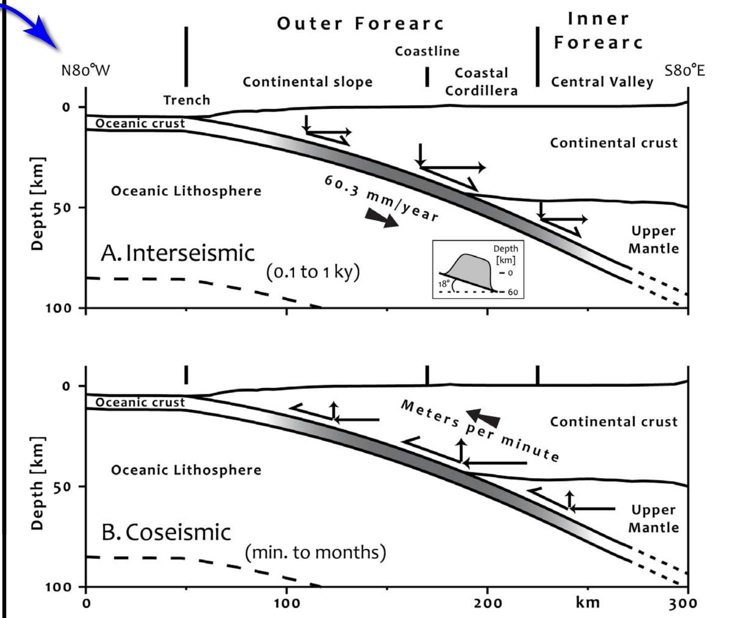
The Maule Earthquake



Ellipse encloses the rupture area. Arrows are long term strain orientation. The box depicts the Pichilemu sequence area. Red lines represent upper crustal faults from the 1-million Chilean Geological map. Dots are upper/lower crust aftershocks (color code explained below).



The Subduction Seismic Cycle

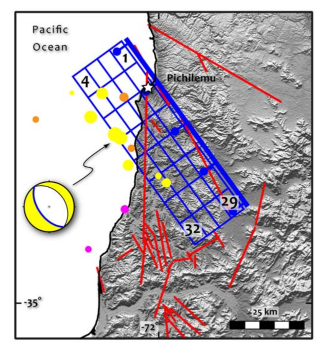


The figure shows the schematic orientation of the external (boundary) shear loads, denoted by black thin arrows, applied at the bottom of the upper plate during the interseismic (A) and coseismic (B) periods

Pichilemu normal fault

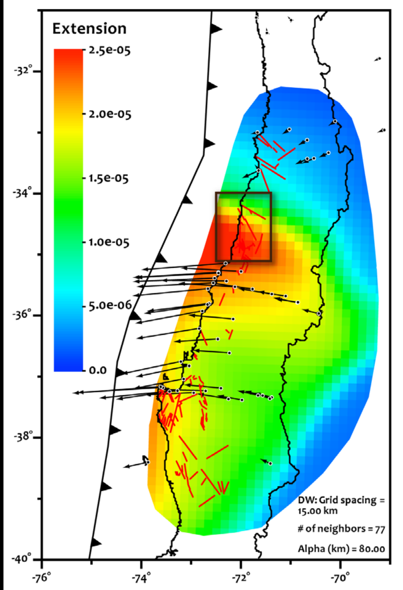
The blue grid delineates the horizontal projection of the subdivided normal fault modeled in this study.

The Coulomb stress increment (CSI) were computed using the Matlab code Coulomb 3.2 (Team Coulomb, USGS).

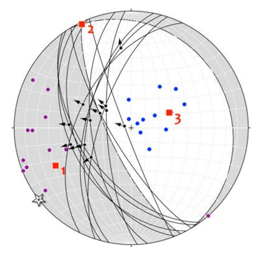


ASTER GDEM (METI and NASA)

Static coseismic GPS strain field & moment tensor sum

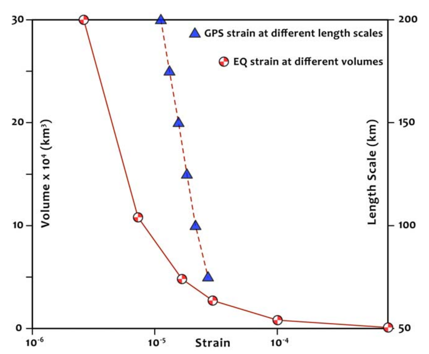


GPS data from Vigny et al. (2011)



Kinematics of the Pichilemu aftershock sequence.

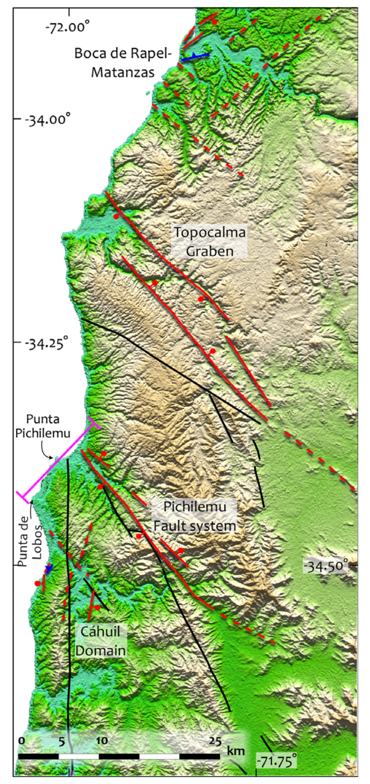
(1) principal extension axis, (3) principal shortening axis, and (2) intermediate axis (symmetric moment tensor). White star shows the principal infinitesimal extension axis calculated from the seven nearest GPS stations.



Static coseismic strain calculated from an earthquake moment tensor sum for the Pichilemu sequence and from coseismic GPS data.

Graph shows the dependence of the magnitude of the coseismic strain on the volume of the region (in the case of earthquakes) or distance weighting factor (in the case of GPS). Nonetheless, for seasonal volumes and length scales, the strain from both earthquakes and coseismic GPS is on the order of 10-4 to 10-5.

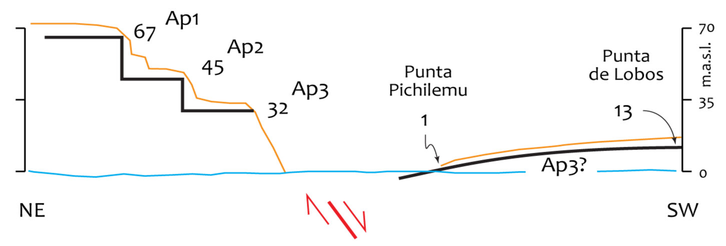
Structural Geology of the Pichilemu Region



Red lines: normal faults (solid: from direct measurements; dashed: inferred from indirect sources), blue lines: reverse faults and black: faults from the 1-million Chilean geological map (SERNAGEOMIN, 2003). Pink line: cross section on the right.

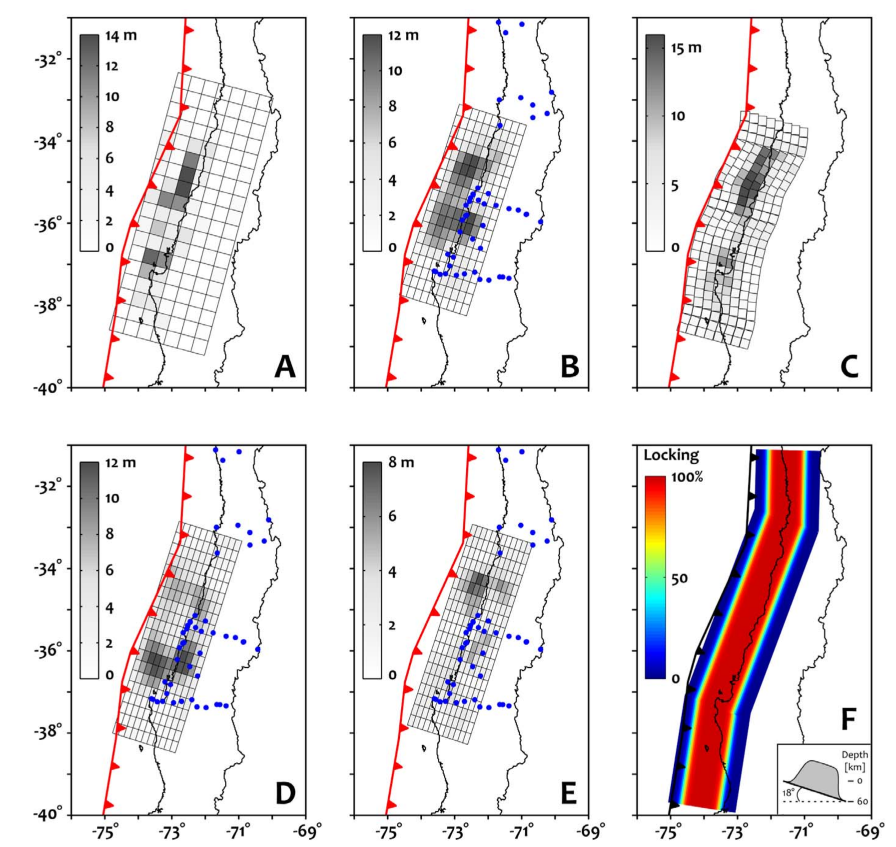
Fault plane of the structure that bounds the southern side of the Topocalma graben. The left side of the picture shows the fault breccia and relicts of the hanging-wall.

Inset shows a close up of the striated and stepped fault plane.



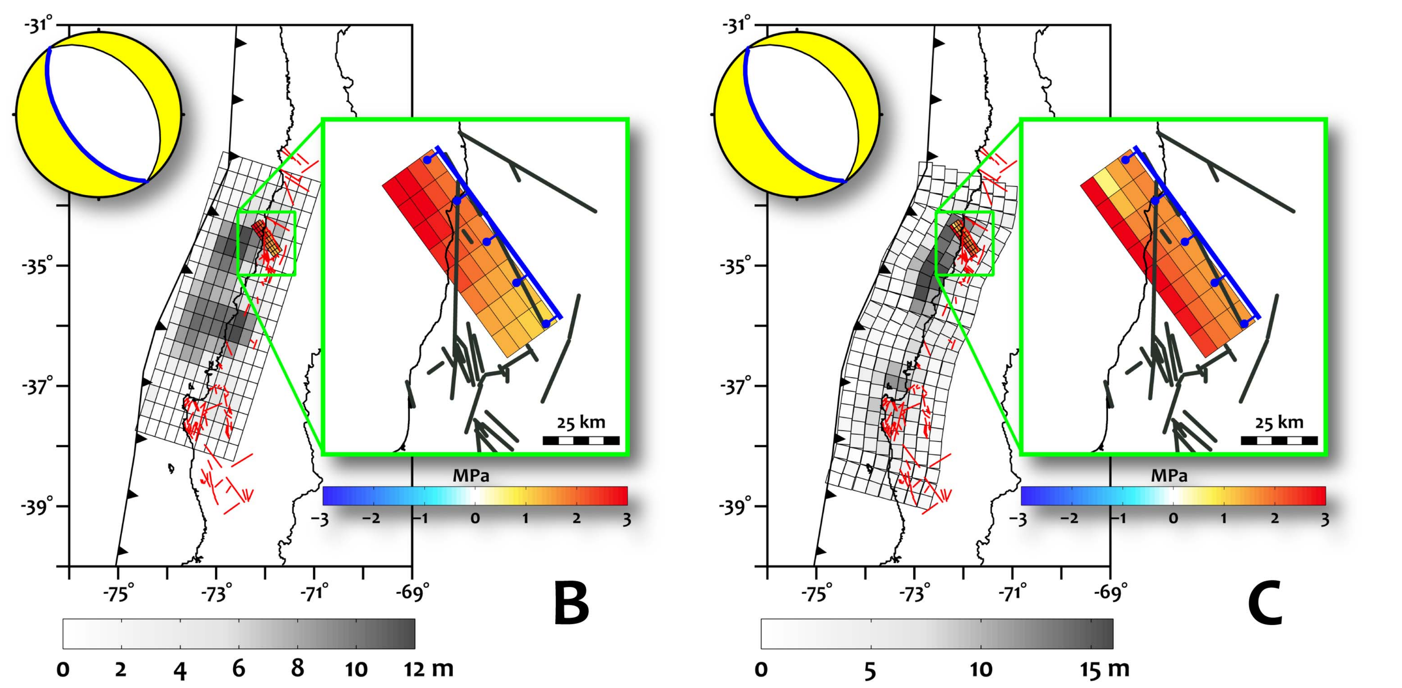
Offset of a Pleistocene marine abrasion platform (Ap; black line) by the Pichilemu normal fault. This geological marker develops a roll-over anticline in the hanging-wall and probably lies at 32 m.a.s.l. in the foot-wall. Repeated reactivations of the structure have created a flight of terraces in the foot-wall (Ap 1-3). Numbers are in meters above the sea level.

Input parameters: Published slip models, coseismic GPS and interseismic locking



A. Delouis et al. (2010), B. Hayes (2010a), C. Lorito et al. (2011), D. Shao et al. (2010), E. Sladen (2010) and F. synthetic interseismic coupling. Since the coseismic slip doesn't have a unique solution, we tested all the available models in order to assess a statistical range of solutions to our mechanical modelling.

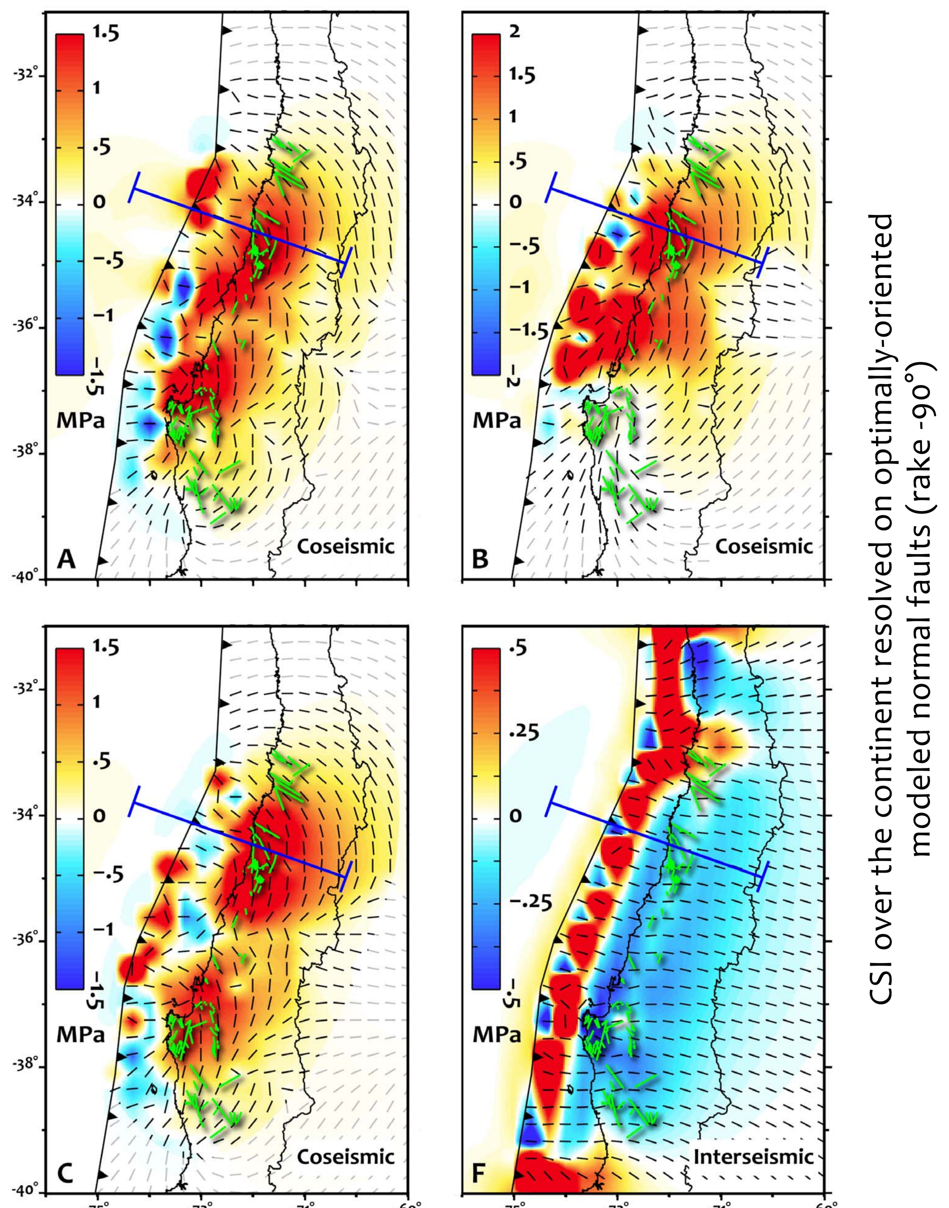
Coseismic Coulomb stress increment (CSI) on Pichilemu fault



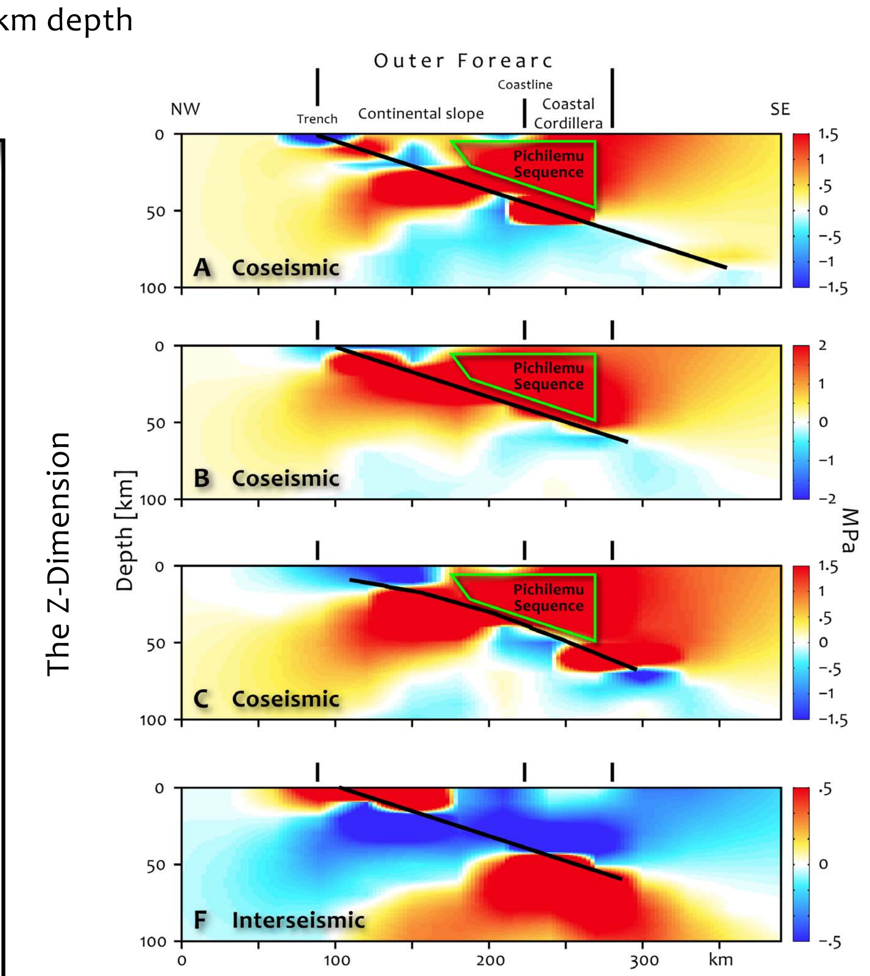
R E S U L T S

- Elastic Vs Permanent: GPS coseismic extension and the strain due to the Pichilemu earthquakes have very similar orientations and are well within an order of magnitude of each other.
- By varying the model inputs we obtained positive CSI averaged across the Pichilemu fault that range from 0.4 to 2.3 MPa.
- The kinematic models produce a semi-elliptical, radial pattern of static extension (predominantly trench perpendicular) enclosing the rupture area and zones of maximum slip.
- Model-generated normal faults also delineate elliptical patterns, meaning that the minimum principal stress axes agree with the direction of extension. The entire outer fore arc wedge has positive CSI values (>0.5 MPa).
- More importantly, the modeled strikes fit the upper crustal structures.
- Interseismic deformation suppress normal faulting in the upper crust wedge (negative CSI). For most of the Coastal Cordillera the optimal modeled orientation disagrees with the structural grain.

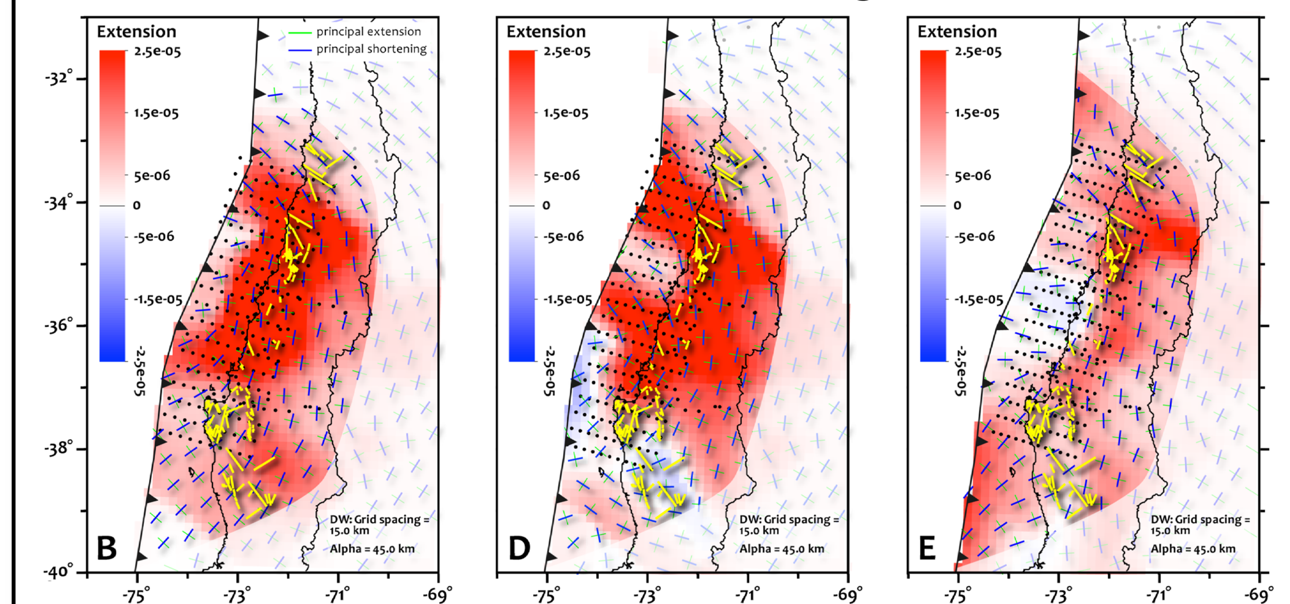
Regional CSI above the Maule rupture



Maps at 10 km depth

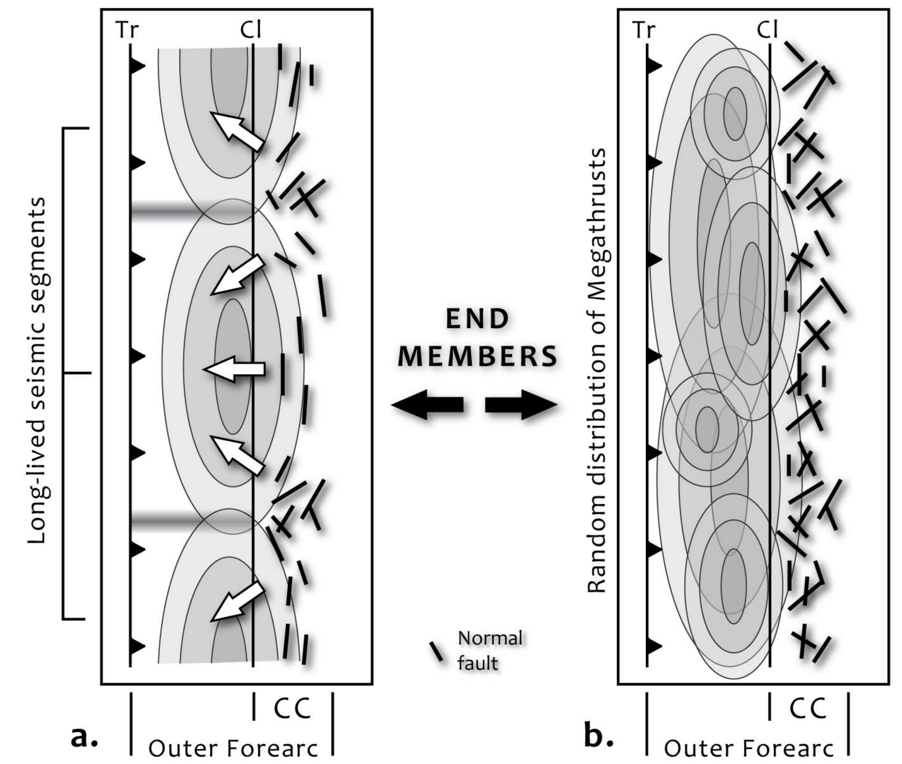


Regional coseismic infinitesimal strain field above the Maule segment



Input data: Static coseismic GPS displacements and slip on the megathrust from teleseismic finite fault models. B. Hayes (2010a), D. Shao et al. (2010) and E. Sladen (2010).

Subduction Seismic Cycles and Long-term Structural Grain



Cartoon showing possible behavior of subduction seismic segments 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. Bimodal orientations occur at 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.

C O N C L U S I O N S

The static coseismic deformation field, imposed in the upper plate by a great subduction earthquake, is an effective mechanism to generate 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 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 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.

Such architectural pattern may be persistent over the Neogene in the region overlying the Maule rupture zone. We suggest that the semi-elliptical outline of the first-order structures along the Coastal Cordillera may indicate cyclic accumulation of slip on long-lived seismic segments. Great earthquakes appear to have ruptured the Maule segment repeatedly over time, thus enhancing the morphological and structural expression of appropriately-oriented forearc structures.

A C K N O W L E D G M E N T S

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R E F E R E N C E S

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