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GEOLOGICAL NOTE

Outer rise seismicity related to the Maule, Chile 2010 megathrust earthquake and hydration of the incoming oceanic lithosphere

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ABSTRACT. Most of the recent published geodetic models of the 2010 Maule, Chile mega-thrust earthquake (Mw=8.8) show a pronounced slip maximum of 15-20 m offshore Iloca (~35°S), indicating that co-seismic slip was largest north of the epicenter of the earthquake rupture area. A secondary slip maximum 8-10 m appears south of the epicenter west of the Arauco Peninsula. During the first weeks following the main shock and seaward of the main slip maximum, an outer rise seismic cluster of >450 events, mainly extensional, with magnitudes Mw=4-6 was formed. In contrast, the outer rise located seaward of the secondary slip maximum presents little seismicity. This observation suggests that outer rise seismicity following the Maule earthquake is strongly correlated with the heterogeneous coseismic slip distribution of the main megathrust event. In particular, the formation of the outer-rise seismic cluster in the north, which spatially correlates with the main maximum slip, is likely linked to strong extensional stresses transfered from the large slip of the subducting oceanic plate. In addition, high resolution bathymetric data reveals that bending-related faulting is more intense seaward of the main maximum slip, where well developed extensional faults strike parallel to the trench axis. Also published seismic constraints reveal reduced P-wave velocities in the uppermost mantle at the trench-outer rise region (7.5-7.8 km/s), which suggest serpentinization of the uppermost mantle. Seawater percolation up to mantle depths is likely driven by bending related-faulting at the outer rise. Water percolation into the upper mantle is expected to be more efficient during the co-seismic and early post-seismic periods of large megathrust earthquakes when intense extensional faulting of the oceanic lithosphere facilitates water infiltration seaward of the trench.

Keywords: Nazca plate hydration, Outer Rise, Maule earthquake, Seismic cycle.

RESUMEN. Sismicidad 'outer rise' relacionada con el mega terremoto de Maule, Chile en el 2010 e hidratación de la litósfera oceánica subductante. La mayoría de los modelos geodésicos del terremoto de 2010 en la Región del Maule, Chile (Mw=8.8) muestran un pronunciado deslizamiento máximo de 15-20 m frente a las costas de Iloca (~35°S), indicando que el mayor deslizamiento cosísmico fue en la parte norte del área de ruptura. Un deslizamiento secundario, con un máximo de 8-10 m aparece al sur del epicentro, localizado al sur de la península de Arauco. Durante las semanas siguientes al evento principal y frente al área de máximo deslizamiento, se formó un enjambre sísmico de más de 450 eventos, con mecanismo de foco mayoritariamente extensional y de magnitudes Mw, oscilando entre los 4 y 6 grados. En contraste con ello, el área del 'outer rise', ubicada frente a la zona sur de deslizamiento máximo, presenta baja sismicidad. Esta observación sugiere que la sismicidad 'outer rise' posterior al evento principal del terremoto del Maule está fuertemente correlacionada con la distribución heterogénea de deslizamiento cosísmico. En particular, la formación del enjambre de sismicidad 'outer rise' en el norte, que se correlaciona espacialmente con el máximo deslizamiento, probablemente está relacionado con fuertes esfuerzos extensionales transmitidos debido al gran deslizamiento de la placa oceánica subductante. Adicionalmnete, datos batimétricos de alta resolución revelan que el fallamiento producto de la curvatura de la placa es más intenso frente al máximo deslizamiento principal, donde se encuentran fallas extensionales

bien desarrolladas en dirección paralela a la fosa. Modelos sísmicos publicados revelan una reducción de la velocidad de onda P en la parte superior del manto oceánico en la región del 'outer rise' (7.5-7.8 km/s), que sugiere serpentinización del manto superior. Percolación de agua de mar hasta profundidades mantélicas es probablemente conducida debido al fallamiento relativo a la torsión de la placa en el outer rise. Es esperable que la percolación de agua hasta el manto superior sea más eficiente durante los períodos cosísmico y el postsísmico temprano de grandes terremotos de contacto, cuando un intenso fallamiento extensional de la litosfera oceánica facilite la infiltración de agua en la zona ubicada en la dirección hacia el océano desde fosa.

Palabras clave: Hidratación de la placa de Nazca, 'Outer rise', Terremoto de Maule, Ciclo sísmico.

1. Introduction

The occurrence of megathrust earthquakes has a profound impact on the regional intraplate stresses in the vicinity of the rupture area. In particular, in the outer rise, which is formed as a consequence of the plate bending of the oceanic plate prior to its subduction. Outer rise seismicity is strongly correlated with variations in interplate coupling, reflecting the stress state of the interplate coupled zone (Christensen and Ruff, 1988). Because regional horizontal stresses vary through the seismic cycle of the interplate megathrust (Taylor *et al*., 1996), with compression in the late interseismic period and tension in the coseismic period, Christensen and Ruff (1988) proposed that compressional outer rise events take place seaward of locked sections of the interplate coupling, whereas tensional outer rise follow large understhrusting earthquakes, as shown in figure 1. However, since the magnitude of coseismic slip along the subduction interface is highly heterogeneous, high seismicity clusters are expected in front of asperities and lacking in zones adjacent to non-asperities, positioned relative to the direction of the plate motion (Dmowska and Lovison, 1992).

The most recent large Chilean earthquake, occurred on February 27th, 2010 (Mw = 8.8), is an example of a large megathrust event caused by the subduction of the oceanic Nazca plate beneath the overriding South American plate. The earthquake rupture propagated northward and southward achieving a final rupture length of about 450 km (34°-38°S) (*e.g*., Moreno *et al*., 2010). The rupture area of this megathrust event is characterized by two regions of high co-seismic slip (asperities) (Delouis *et al*., 2010; Lay *et al*., 2010; Lorito *et al*., 2011; Pollitz *et al*., 2011). Between these asperities, the rupture bridged a zone that was creeping interseismically with consistently low co-seismic slip. The bilateral rupture propagated towards the south, where one asperity failed, and bridged a previously

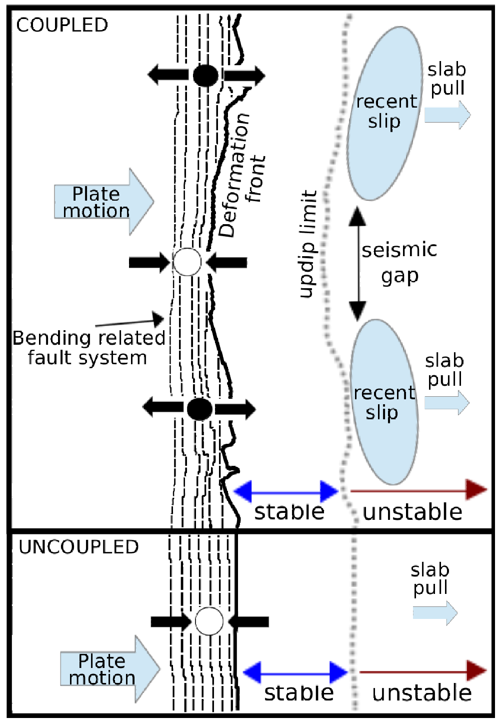

FIG. 1. Conceptual model of the relationship between coupled/uncoupled subduction zones and outer rise earthquake mechanisms in central Chile, based in the model given by Moscoso *et al*. (2011) and in the idealized mechanism proposed by Christensen and Ruff (1988). Compresional outer rise earthquakes are represented by black circles, extensional events are drawn as white circles and the black arrows show the orientations of the main stress axes. After Christensen and Ruff (1988).

creeping zone to the north, where a second asperity failed (Moreno *et al*., 2010). The northern asperity, however, concentrates most of the co-seismic moment of the Maule megathrust earthquake with maximum co-seismic slip of 15-20 m (Delouis *et al*., 2010; Lay *et al*., 2010; Lorito *et al*., 2011; Pollitz *et al*., 2011).

In order to understand the impact of the co-seismic slip distribution of this megathrust earthquake on outer rise seismicity before and after the main shock, we compile seismological data from the USGS (NEIC) and Harvard (CMT) catalogs at the outer rise seaward of the rupture area of the megathrust Maule earthquake. In addition, high resolution bathymetric data and published seismic constraints are used to study the impact of plate bending on faulting and hydration of the upper oceanic lithosphere. Our observations, based on available data, provide new insights in how the occurrence of a megathrust event affects the stress regime in the outer rise area, and how this is closely related to the hydration process of the upper oceanic lithosphere.

2. Outer Rise Seismicity

The Chile Subduction zone is characterized by outer rise seismicity ranging from micro (Mw< 2; Tilmann *et al*., 2008) to intermediate and large earth-quakes (4 ≤ Mw ≤ 7; Clouard *et al*., 2007). The outer rise events occurring at shallow (<10 km) and intermediate (<40 km) depths are attributed to outer rise faulting, triggered by the bending of the incoming plate. View along a profile perpendicular to the trench axis, this results in extensional and compressional seismicity in its shallow and deeper part, respectively. The location of the neutral stress plane, which defines where the stress regime in the lithosphere changes from tensional to compressional, is presumably thermally controlled by the depth of the 350°-450°C isotherm (*e.g*., Seno and Yamanaka, 1996). Near 32°S, the outer rise seismicity might also be influenced by a complex fault system produced by the stress field perturbation induced by the subduction of the Juan Fernández Ridge (JFR) (Clouard *et al*., 2007)

We compared the seismic activity present in the area from 2 years prior the main shock and the aftershocks reported up to three months after, considering that this time frame is reasonable for driving conclusions about the seismic cycle. It is clearly seen in figure 2A that during the years previous to the main shock, the seismicity on- and off- shore Maule presented little activity in comparison with other segments of the Chilean subduction zone. The largest outer rise event recorded in the late interseismic period of the megathrust Maule earthquake, occurred almost seven years before the main shock, on 28/2/2003, when a Mw=5.3 at ~15 km depth compressional event (CMT catalog) ruptured the upper part of the oceanic lithosphere offshore Constitución.

The previously described behavior changed radically after the megathrust Maule earthquake. Within the three months after the 27th of February, almost 480 outer rise events of Mw > 4 were reported by NEIC catalog in the trench outer rise area (Fig. 2B). A cluster of high seismicity between the 33.5°S and 35.5°S was formed in the outer rise, figures 2C and 2D show that this cluster is coincident with the northern maximum co-seismic slip of the Maule earthquake (*e.g*., Lorito *et al*., 2011). Within the year following the Maule earthquake, six tensional outer rise events Mw > = 5.0 were reported offshore central Chile by CMT catalog and they are also located seaward of the northern maximum slip (Fig. 2B).

3. Outer Rise faulting and Hydration of the upper oceanic lithosphere

For the area between 33°S and 39°S, the seafloor spreading fabric of the incoming Nazca plate trends approximately N50W. In the outer rise area, the seafloor fabric generated at the spreading center and cross-cutting normal faults caused by plate bending are well imaged by multibeam bathymetric data (Fig. 3); whereas bend-faults strike approximately parallel to the trench axis and form a new fabric. The Nazca plate in south central Chile is influenced by the existence of JFR, it perturbates the regional stress field (Ranero *et al.,* 2005) and produces inheterogeneities of the seismicity of the Nazca plate when approaches the continent (Clouard *et al.*, 2007). This produces that the fault system is not perfectly parallel to the trench. In particular, we distinguish two different areas, north of the epicenter which presents intensive faulting with well developed extensional faults (Fig. 3A) and south of the epicenter where fracturing is less pronounced (Fig. 3B).

The structure of the outer rise area between 34°S and 35°S was revealed by the seismic profile P03, which runs perpendicular to the trench (Figs. 2A and 2B). The model was derived from wide angle seismic data, retrieved in 2008, and the structure of the overriding plate was interpreted by Moscoso *et al*. (2011). Their results show that the ~6 km thick incoming oceanic crust is characterized by a reduction of lowermost crustal velocities from ~7.1 km/s to >6.8 km/s towards the trench (Fig. 4). Uppermost mantle velocities are remarkably lower (7.5-7.8 km/s) than

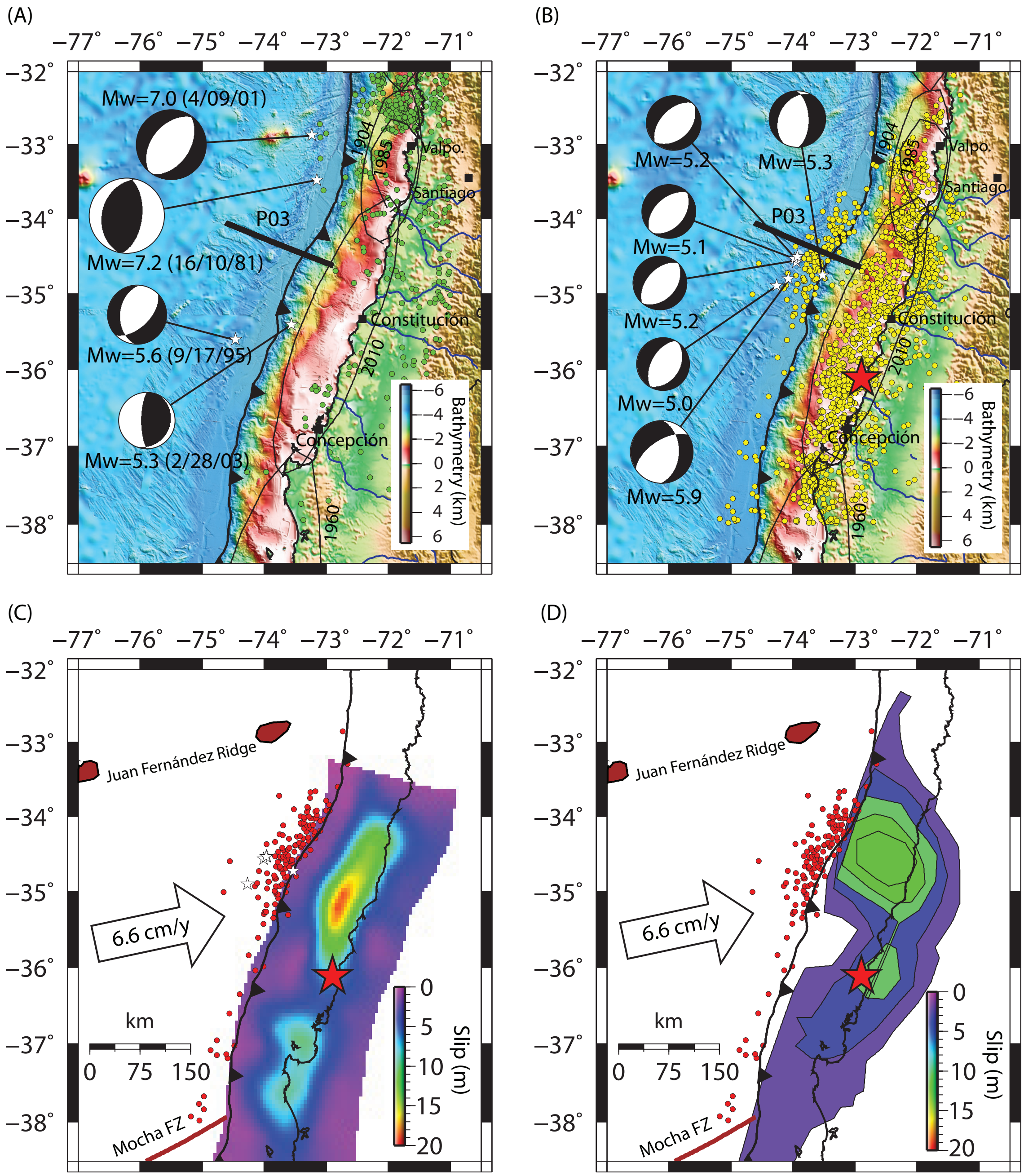

FIG. 2. **(A)** and **(B)** show the Bathymetric/Topographic map of central Chile. The green dots in (A) correspond to the seismicity reported by NEIC catalog with magnitude higher than 4 from 1/1/2008 until the day before hit the Maule earthquake on 27/2/2010. In figure (B), the yellow dots stand for the aftershocks reported by NEIC catalog up to three months after the main shock of the Maule earthquake. We also show the CMT focal mechanisms of the most significant outer rise earthquakes prior to the 2010 earthquake in (A) and of the aftershocks with Mw>5.0 reported by CMT catalog during the year following the Maule earthquake. For comparison, we show the coseismic slip models, after (C) Lorito *et al.* (2011) and (D) Lay *et al*. (2010), and its correlation with the trench outer rise seismic activity after the earthquake presented in (B). From figures **(C)** and **(D)** it is evident the change of outer rise earthquake type to pure tensional regime after the Maule earthquake. The arrow of figures (C) and (D) indicates the convergence velocity between the Nazca and South American plates (Angermann *et al*., 1999). The red dots denote the aftershocks reported by NEIC catalog up to three months after the main shock of the Maule earthquake.

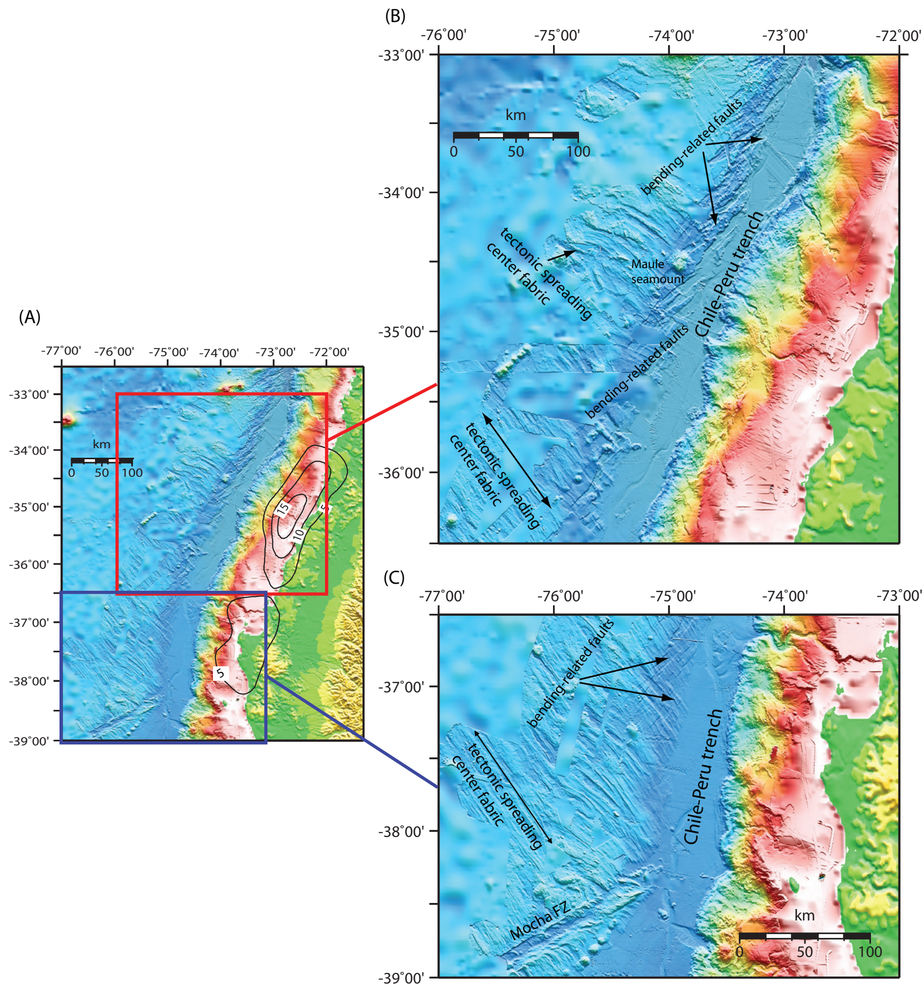

FIG. **3.** **(A)** High-resolution bathymetric image of the seafloor offshore central Chile (Flueh and Bialas, 2008; Ranero *et al*., 2005; Voelker *et al*., 2009; Moscoso *et al*., 2011). Note the SE-NW trending topographic pattern of the tectonic fabric formed at the East Pacific spreading center, which is overprinted by bending related faults. Slip contour lines are based on the coseismic slip model of Lorito *et al*. (2011), shown in figure 2C. Bending related faults trend roughly parallel to the trench axis, where faulting appears to be more intense in the north **(B)** than in the south **(C)** of the epicenter of the Maule earthquake.

average upper mantle velocities (≥8.0 km/s) and coincident with an evident crustal Vp reduction in the trench-outer rise region. This Vp reduction, is also obseved along strike (Contreras-Reyes *et al*., 2007, 2008) and is an evidence of hydrothermal circulation produced by the infiltration of seawater through the fault system (Ranero *et al*., 2005).

4. Discussion and Conclusions

A seismic asperity is an area with locally increased friction and exhibits little aseismic slip during the interseismic period relative to the surrounding regions. Once the shear yield stress (critical shear stress required for failure) along these heterogeneities is reached by the accumulated interseismic shear stress, the asperity concentrates the coseismic moment release and slip during the earthquake (Aki, 1979; Kanamori and McNally, 1982). In particular, the northern area of the Maule earthquake presents the main seismic asperity of the event according to the geodetical models (Lay *et al*., 2010; Moreno *et al*., 2010; Lorito *et al*., 2011; Pollitz *et al*., 2011). On the other hand, Dmowska *et al.* (1988) and

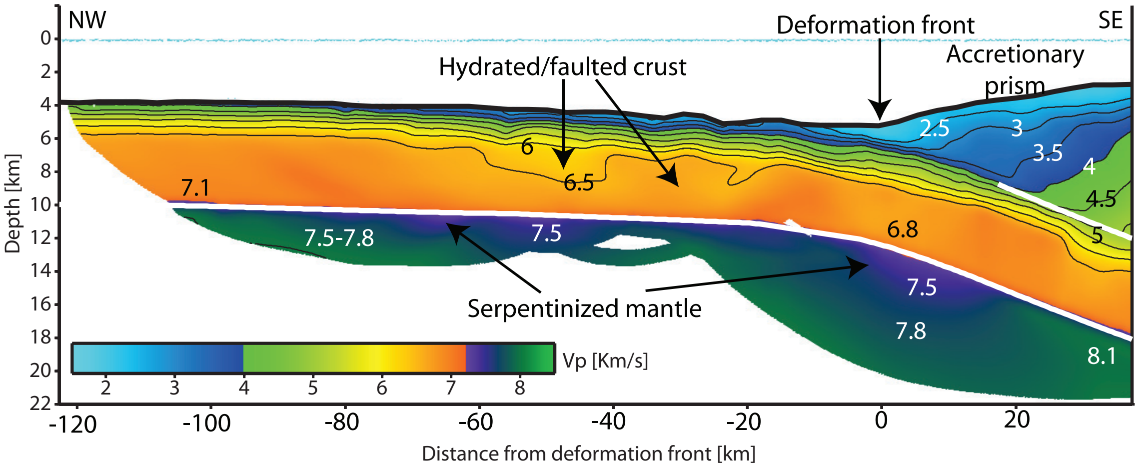

FIG. 4. Seismic velocity model of P03 after Moscoso *et al*. (2011). Relative low mantle and crustal velocities in the trench outer rise region, suggesting intense bending related fracturing and seawater infiltration into the oceanic lithosphere.

Dmowska and Lovison (1992) proposed that high outer rise seismicity usually develops seaward of the main asperity following the megathrust event. This was the case of the Maule earthquake, where the maximum co-seismic slip distribution (main seismic asperity) correlated fairy well with the high outer-rise seismicity cluster, located roughly between 34°S-35°S (Fig. 2).

The strong spatial correlation between the northern maximum coseismic slip and outer rise seismicity following the Maule megathrust earthquake shown in figure 2, suggests that tensional stresses are transferred in a more effective manner in regions seaward of large co-seismic slip. During the co-seismic period, due to the underthrusting motion, slab pull forces are transmitted seawards through the plate, reactivating and possibly creating new normal faults at the trench-outer rise, thus producing tensional outer rise events (Christensen and Ruff, 1988). In the interseismic period, the high stress accumulation over more than a century in the Constitución-Concepción seismic gap was evidenced by 10 m slip deficit (Ruegg *et al*., 2009). The high coupling at the subduction interface favored the occurrence of some compressional outer rise events, characteristic of mature seismic gaps (Christensen and Ruff, 1988). The idea exposed by Christensen and Ruff (1988) that a change between outer rise compression and tension is produced by a change between stress accumulation and release after the occurrence of a large thrust earthquake, is supported by our observation of a change of the outer-rise earthquake focal mechanisms from compressional in the interseismic to extensional in the co-seismic (Figs. 2A and 2B).

In addition, seaward of the main seismic asperity, outer rise faulting is intense as is evidenced by well developed extensional faults. The outer-rise faulting pattern, well-developed in the north (34°S-36°S) and less developed in the south (>36°S-39°S), suggests that the high seismicity at the outer rise is a long term feature that characterizes the seismic cycle of the Maule subduction zone. Thus, if outer rise faulting is indeed a consequence of effective transference of extensional stresses during the coseismic period of megathrust events, then the subduction interface in the Maule region is, for a long term, highly coupled during interseimic periods.

It is also expected that during the coseismic and early postseismic period of large megathrust earthquakes, activation of bending-related faults occur forming pathways for seawater percolation. A plausible interpretation for the low crustal and uppermost mantle velocities, observed in the seismic model of figure 4, is that water percolation through bending-related faults leads to mineral alteration and hydration of the oceanic crust and mantle (Grevemeyer *et al.*, 2007; Contreras-Reyes *et al.*, 2008). Uppermost mantle velocities of ~7.5 km/s are much lower than typical mantle peridotite, suggesting a mantle serpentinization of ~10-20%. We suggest that the amount of seawater percolated into the lithosphere is more effective during the co-seismic period of large megathrust earthquakes, when intense extensional faulting of the oceanic lithosphere at the trench outer rise facilitates water infiltration.

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SUPPLEMENTARY MATERIAL

In order to show the extension of the outer rise high and low fracturing zones in the north and south of the study area, respectively, we performed a pattern recognition using the convolution between the bathymetrical image and the kernel:

$$\begin{bmatrix} -1 & -1 & 1 \\ -1 & 4 & -1 \\ 1 & -1 & -1 \end{bmatrix}$$

The results of figure A1, presents the bathymetry (left) and the results of the convolution (right) in gray-scale from 0 (black) to 255 (white).

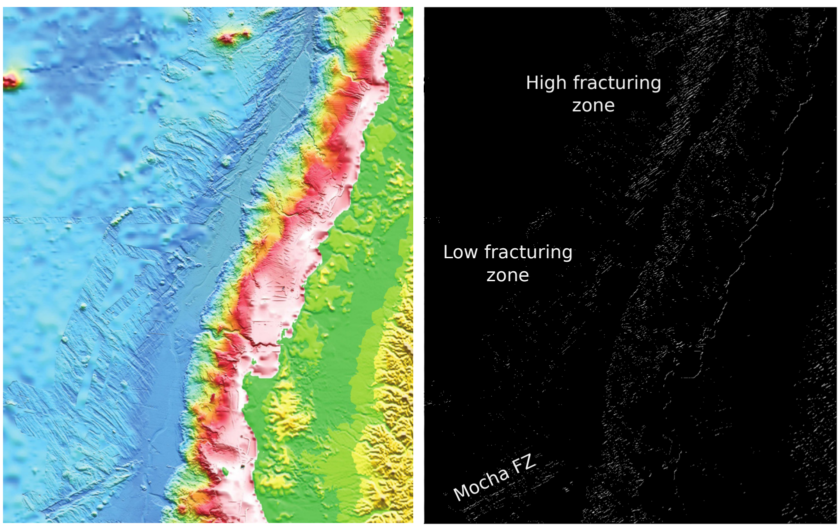

FIG. A1. Extraction of possible faults in the bathymetry, confirming that the southern part of the study area has a less intense outer rise fracturing than the northern part.