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Key Points:

- Seismogenic behavior of subduction megathrust may be affected by materials derived from the base of the serpentinized forearc mantle wedge
- Thermopetrologic modeling suggests abundance of lizardite and chrysotile around the mantle wedge corner but antigorite farther down dip
- Serpentine frictional behavior may explain distributions of stress drop and seismic energy radiation in 2010 rupture and aftershocks

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Role of Serpentinized Mantle Wedge in Affecting Megathrust Seismogenic Behavior in the Area of the 2010 $M = 8.8$ Maule Earthquake

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Abstract What controls subduction megathrust seismogenesis down dip of the mantle wedge corner (MWC)? We propose that, in the region of the 2010 $M_w = 8.8$ Maule, Chile, earthquake, serpentine minerals derived from the base of the hydrated mantle wedge exert a dominant control. Based on modeling, we predict that the megathrust fault zone near the MWC contains abundant lizardite/chrysotile-rich serpentinite that transforms to antigorite-rich serpentinite at greater depths. From the MWC at 32–40 km depth to at least 55 km, the predominantly velocity-strengthening megathrust accommodated dynamic propagation of the 2010 rupture but with small slip and negative stress drop. The down dip distribution of interplate aftershocks exhibits a gap around the MWC that can be explained by the velocity-strengthening behavior of lizardite/chrysotile. Interspersed velocity-weakening and dynamic weakening antigorite-rich patches farther down dip may be responsible for increased abundance of aftershocks and possibly for some of the high-frequency energy radiation during the 2010 rupture.

Plain Language Summary A subduction megathrust rupture may extend from the trench to beneath populated coastal area. To understand what controls the megathrust seismogenic behavior of its deeper part, we conduct a case study of the 2010 magnitude 8.8 Maule, Chile, earthquake and its aftershocks. With numerical thermal modeling, we find that the deep seismogenic behavior may be controlled by serpentine materials derived from the base of the overlying hydrated mantle wedge. The deep part of the megathrust ruptured “passively” against increasing resistance (negative stress drop). Lower-temperature serpentines lizardite and chrysotile that are known to facilitate aseismic slip may be responsible for an observed gap in aftershock distribution in the down dip direction. Higher-temperature serpentine antigorite that is known to facilitate seismic slip may be responsible for increased aftershocks farther down dip and possibly radiation of high-frequency energy during the 2010 Maule earthquake.

1. Introduction

The seismogenic behavior of subduction megathrusts depends on the mechanical properties of the plate-boundary fault zone. The fault zone hosts a mélange of materials derived from both the subducting and overriding plates and undergoes localized or distributed shear in its different parts (Agard et al., 2018; Guillot et al., 2015; Hirauchi et al., 2020; Rowe et al., 2013). Because the fault zone composition and structure vary spatially as controlled by the thermal state and the geological characteristics of the incoming and overriding plates, its seismogenic behavior is expected to vary accordingly. The behavior may be dominated by subducted sediments in one area but by oceanic basalt in another area. In this paper, on the basis of earthquake observations and thermo-petrological arguments, we propose that the slip behavior of the deeper part of the rupture area of the 2010 $M_w = 8.8$ Maule, Chile, earthquake (Figure 1a), and probably other segments of the Chilean margin, is strongly affected by hydrous minerals present at the base of the overriding mantle wedge.

Hydrous minerals such as serpentine, talc, and chlorite form in the forearc mantle wedge with the addition of aqueous fluids from the subducting slab (Hyndman & Peacock, 2003; Reynard, 2013). In warm subduction

Figure 1. Megathrust slip and stress drop distributions in the 2010 $M_w = 8.8$ Maule earthquake. (a) Average of eight published coseismic slip models (Benavente & Cummins, 2013; Delouis et al., 2010; Luttrell et al., 2011; Moreno et al., 2012; Pollitz et al., 2011; Pulido et al., 2011; Vigny et al., 2011; Yue et al., 2014). Black and gray dots show best quality and other, respectively, aftershock epicenters from Lange et al. (2012). The green curves show the 0.5 and 1.0 m slip contours of the 2012 $M_w = 7$ earthquake, with the red and blue circles marking its nucleation center and primary epicenter, respectively (Ruiz et al., 2013). Blue line marks the main profile discussed in this paper, with the wider portion showing the distance range of Figure 2a. Subduction interface depth (Hayes et al., 2012) is contoured in km (light blue curves). (b) Stress drop derived from the average slip shown in (a) using the method of Brown et al. (2015). The dark blue curve outlines the area of high-frequency seismic radiation reported by Lay et al. (2012) based on 0.5–5 Hz waveforms, and the yellow circles represent radiation peaks determined by Palo et al. (2014) using 1–4 Hz waveforms. Estimated Moho or V_p profiles based on previous studies along the three roughly margin-normal dashed profiles are shown in Figure 2b (see Figure 2b for explanation of color coding).

zones, the tip area of the mantle wedge is expected to be extensively hydrated because of shallow dehydration of the subducting oceanic crust (Gao & Wang, 2017). In most other subduction zones, slab dehydration does not peak until greater depths (Abers et al., 2017; Wada & Wang, 2009), but limited fluids released at shallower depths will produce hydrous minerals at least along the base of the mantle wedge (Agard et al., 2018; Reynard, 2013). In the past, these hydrous minerals were thought to exhibit a velocity-strengthening behavior, so that the mantle wedge corner (MWC) was inferred to represent a downdip limit to megathrust rupture (Hyndman et al., 1997; Oleskevich et al., 1999). However, more recent earthquake observations show rich complexity downdip of the MWC (Lay et al., 2012). The suite of observations from the Maule rupture area provide an excellent opportunity for a case study of the role of the mantle wedge in affecting megathrust seismogenic behavior.

2. Earthquake Observations

2.1. Downdip Extent of the Maule Rupture

The Maule earthquake occurred along the Chile subduction zone where the Nazca plate subducts beneath the South America plate at a rate of ~ 74 mm/yr. Figure 1a shows the average of eight published coseismic slip models derived from geodetic, seismological, and/or tsunami observations. We focus on the margin-normal profile crossing the area of maximum rupture (Figure 1a), along which 12 rupture models are shown in Figure 2a, including those used for Figure 1a. The published slip models are based on highly simplified plate interface geometry, in most cases a single plane. In deriving the average model, we map each slip vector in these models to a common three-dimensional (3-D) plate interface (Hayes et al., 2012) by shifting its depth and rotating it around the local fault strike into the 3-D fault (Brown et al., 2015). The mapped slip vector maintains its horizontal location and magnitude but has a slightly modified depth, dip, and rake to accommodate the 3-D fault geometry.

Figure 2. The 2010 Maule coseismic slip, aftershock distribution, and thermal model along the main corridor shown in Figure 1a. (a) Coseismic slip in the deeper part of the megathrust from the eight models used to derive the average in Figure 1a (solid lines) and four other models (dashed lines) (Fortuño et al., 2014; Hayes et al., 2013; Lin et al., 2013; Lorito et al., 2011). Inset shows the entire profile and the portion displayed in this figure (lower right box). (b) Thermal model (with effective coefficient of friction $\mu' = 0.03$) and side view of aftershocks within 100 km of the profile. Dark blue line is the plate interface as in Figure 1. Black and gray dots are best quality and other, respectively, aftershocks reported by Lange et al. (2012) as in Figure 1a. Although the cluster of seismicity at ~150 distance is shown above the blue line, the vast majority of these events are likely interplate events based on focal mechanism analysis (e.g., Agurto et al., 2012; Lange et al., 2012). The shown V_p contours are for 7.5 km/s (shallower) and 7.75 km/s (deeper). Hicks et al. (2014) used the latter to approximate the Moho. The reddish band marks the possible range of Moho depths (32–40 km) assumed in this study.

Figure 2a shows that the coseismic slip extended to at least 55 km depth, but slip less than 2 m is probably beyond resolution limit. Most of the slip models used Global Navigation Satellite System (GNSS) and interferometric synthetic aperture radar (InSAR) data that were collected a few days to three weeks after the earthquake. However, Vigny et al. (2011) reported that, over 2–3 weeks following the earthquake, coastal GNSS sites underwent postseismic displacements amounting to only 3% of their coseismic displacements.

2.2. Stress Drop Distribution in the Maule Rupture

From the average coseismic slip model (Figure 1a), we have derived the static stress drop distribution along the megathrust (Figure 1b) using the method and procedure of Brown et al. (2015). The stress drop exhibits considerable spatial heterogeneity as expected of any large earthquake, even though the average slip model surely has smoothed out much of the short-wavelength heterogeneity. The stress increase (negative stress drop) in some areas near the trench is poorly constrained for lack of seafloor geodesy, and the narrow strip of stress drop along the trench is a boundary artifact that does not impact the rest of the model. Large, positive stress drops occur at depths shallower than 30–40 km (Figure 1b). Stresses increase downdip of this depth range, indicating that the deeper megathrust participated in the 2010 rupture “passively,” primarily resisting rather than promoting seismic slip.

Lay et al. (2012) and Palo et al. (2014), among others, used back-projection imaging with teleseismic short-period waveforms to delineate the area of the megathrust where high-frequency seismic energy was radiated

during the 2010 Maule rupture (Figure 1b). The reported high-frequency radiation is largely down-dip of the area of stress drop and extends well into the area of stress increase.

2.3. Distribution of Interplate Aftershocks

Aftershocks within 7 months after the main shock recorded by a dense network of 146 stations along the 2010 Maule rupture (Lange et al., 2012) are shown in Figure 1a. Lange et al. (2012) reported 20,189 events, with 13,438 having at least 12 *P* phase recordings and a small subset of 2,494 considered to be of the best quality. In the study of Lange et al. (2012), events were detected using Coalescence Microseismic Mapping (CMM, Drew et al., 2013), an algorithm involving backpropagating STA/LTA based arrival pick probability density functions, and were automatically picked and located using a one-dimensional velocity model and station corrections. Depth uncertainties are estimated to be <5 km for events landward of the coast. In a separate study (Hicks et al., 2014), relocation of Maule aftershocks using a 3-D velocity model made little improvements to event locations beneath their land-based seismic network, although it greatly improved event locations far offshore beyond the network.

The cross-section view of the aftershock distribution within 100 km of the main profile is shown in Figure 2b. Based on focal mechanisms of larger events, derived from either first motions recorded by the local network or global centroid moment tensor solutions, Lange et al. (2012) demonstrated that the events forming the eastward dipping bands were interplate events, whereas the shallow cluster of (normal-faulting) events were located in the upper plate crust. The small separation between the interplate aftershocks and the shown megathrust (Hayes et al., 2012) reflects uncertainties in aftershock depths and/or the megathrust geometry.

The most striking character of the aftershock distribution is that the interplate events are separated into two groups by a gap around the 30–45 km depth range (Figures 1a and 2). The presence of this gap is confirmed by an independent study by Rietbrock et al. (2012). A similar gap is also observed in interplate seismicity in the area of the 2015 $M_w = 8.3$ Illapel earthquake 500 km north of our main profile, both before and after the mainshock (Lange et al., 2016). The location of the seismic gap is not strongly dependent on the velocity model used for earthquake location; similar results were obtained using other one- and two-dimensional velocity models for the Chilean margin (Lange et al., 2012; Rietbrock et al., 2012). A large aftershock of $M_w = 7.0$ in 2012 bridged a small part of the gap in the Maule area (Figure 1a) (Ruiz et al., 2013), an event we will discuss in section 3.4.

3. Role of the Mantle Wedge

3.1. Moho Depth

The down-dip changes in Maule rupture stress drop, aftershock distribution, and possibly the radiation of seismic energy appear to correlate with the MWC. Figure 2b shows the continental Moho near the MWC based on the receiver function (RF) analyses of Dannowski et al. (2013) and Bishop et al. (2019). In Figure 3 of Dannowski et al. (2013), the estimated Moho was drawn about one fourth wavelength below the peaks of the RF waveforms, but here we follow the common practice in RF analysis to use the peaks themselves to define the Moho. The average depth of the peaks at the six stations showing the Moho signal is about 34 km (Figure 2b, green). Bishop et al. (2019) had two other profiles located much farther south, and the one shown in Figure 2b is the nearest to our main profile (Figure 1). In transferring their results to Figure 2b (red), we do not follow the original publication to extrapolate the Moho beyond the westernmost station showing the Moho signal (at ~38 km depth), located at roughly 140 km distance in Figure 3a of Bishop et al. (2019). In accordance with the two RF studies and taking into consideration their uncertainties, we assume the Moho to be in a depth range of 32–40 km (Figure 2b).

Also shown in Figure 2b are the 7.5 and 7.75 km/s *P* wave velocity (*V_p*) contours delineated by Hicks et al. (2014) along a profile coinciding our main profile (Figure 1). Hicks et al. (2014) obtained these values by conducting *V_p* and *V_s* (*S* wave velocity) local-earthquake tomography in the Maule earthquake region. In an idealized setting, either of the two shown *V_p* contours may be used to approximate the Moho. However, the presence of hydrous minerals will decrease seismic velocity in the mantle wedge (e.g., Hyndman & Peacock, 2003). According to Hicks et al. (2014), *V_p* values in the triangular area between the RF-defined Moho and the 7.5 *V_p* contour is of the order of 6.75 km/s and thus may reflect some serpentinization.

Figure 3. Phase diagram of serpentine minerals based on Schwartz et al. (2013) and Evans (2004). Atg = Antigorite, Brc = Brucite, Chr = Chrysotile, Fo = Forsterite, Lz = Lizardite, $\text{SiO}_2(\text{aq})$ = Silica in aqueous fluid, Tlc = Talc. The Lz + Chr to Atg transition shown as a gray band and antigorite breakdown reactions (black solid lines) are as proposed by Evans (2004). The Lz + Chr to Atg transition through reaction (1) or (2) shown using paired brown and green lines (start and end of reaction) was obtained by Schwartz et al. (2013) based on Alpine serpentinite: Solid portions of the reaction boundaries reflect the $P \sim 1$ GPa metamorphic pressures recorded by Alpine metamorphic rocks, whereas the dashed portions are extrapolations to higher and lower pressure. Maule megathrust temperatures (shown in blue color) are predicted by thermal models of this work using different values of effective coefficient of friction μ' . The Moho depth range is as in Figure 2.

Given the limited resolution of tomographic imaging, we refrain from more quantitatively inferring the degree of serpentinization from the V_p and associated V_p/V_s ratio values reported by Hicks et al. (2014).

The Maule rupture as determined by slip inversion extended far down-dip of the MWC, but the deeper megathrust acted to resist rupture propagation, resulting in stress increase, diminished slip, and possibly higher-frequency radiation (Figures 1 and 2a). Aftershocks decrease in abundance near the MWC compared to updip and downdip portions of the megathrust (Figure 2b). Because of the focus of this paper, we do not discuss rupture and aftershock processes updip of the MWC.

3.2. The Thermo-Petrologic Field

To understand the role of the MWC in controlling the slip behavior summarized in section 2, we construct a two-dimensional finite element thermal model along the main profile (Figure 2b) to predict mantle wedge petrology and how it may affect megathrust friction. The modeling procedure is exactly as described in Gao and Wang (2014), except for a slight update in seafloor topography. The results are thus nearly identical to their Central Chile model. The thermal structure of the incoming Nazca plate is based on its age at the trench (32 Ma). The maximum depth of decoupling (MDD) between the slab and the mantle wedge is assumed to be 75 km (Wada & Wang, 2009). The mantle wedge is assigned a dislocation creep rheology and is driven to flow by the slab via coupling downdip of the MDD. Following Gao and Wang (2014), we assume an effective coefficient of friction $\mu' = 0.03$ for the shallow, frictional part of the interface, but we also vary μ' by 50% to test model sensitivity. The reader is referred to Gao and Wang (2014) for other parameters and methodological details.

Model-predicted temperatures along the subduction interface are shown in Figure 3, together with values predicted with two other values of μ' .

At depths greater than the continental Moho, the predicted interface temperatures pertain to the base of the mantle wedge and therefore can be compared with the stability fields of hydrous minerals in ultramafic rocks. The most relevant part of the hydrous ultramafic phase diagram is depicted in Figure 3. At depths greater than our assumed Moho, the low- T serpentine minerals lizardite and chrysotile react to form the high- T serpentine mineral antigorite at 300–400°C based on Schwartz et al.'s (2013) detailed study of Alpine serpentinites where accurate P - T conditions for serpentinite reactions were determined from adjacent metasedimentary rocks (brown and green lines). The transformation of lizardite to antigorite is sluggish and involves different potential reactions as depicted in Figure 3. Chrysotile is thermodynamically metastable, but is commonly observed in low-temperature lizardite serpentinites (Evans, 2004). In subduction zones, lizardite/chrysotile- and antigorite-rich serpentinites commonly contain other hydrous platy minerals, such as chlorite, talc, or brucite. Talc, in particular, will be common in parts of the mantle that have reacted with Si-rich aqueous fluids. Given a continental Moho depth of 32–40 km, the base of the mantle wedge in the Maule area is expected to be rich in lizardite/chrysotile near the MWC but consist primarily of antigorite further downdip (Figure 3).

3.3. Effects of Serpentine on Slip Behavior

Mantle wedge petrology is relevant to megathrust friction because materials derived from the base of the mantle wedge are incorporated into the fluid-rich megathrust fault zone (Agard et al., 2018; Scambelluri et al., 2019). For warm-slab subduction zones, the most seaward part of the mantle wedge is expected to be extensively serpentinized (Abers et al., 2017; Gao & Wang, 2017). Despite the large volume increase associated with serpentinization, a conspicuous topographic expression of associated uplift is not observed, probably because serpentinite is frequently removed from the wedge base to form serpentine-rich lenses or patches in the megathrust shear zone. Since serpentinite likely exists along the base of the mantle wedge in

Figure 4. Schematic illustration of the conceptual model proposed in this work for the Maule region. Seismic rupture updip of the MWC (gray patches) is not discussed in this paper. Downdip of the MWC, the shallower zone rich in lizardite (and chrysotile) is responsible for the paucity of interplate aftershock (Figure 2), and the deeper antigorite-rich patches are responsible for abundant aftershocks (Figure 2) and possibly also for the high-frequency radiation during the Maule rupture (Figure 1c). In the bottom illustration, white areas along the plate interface are velocity-strengthening (shallow) or viscous (deep). Within the mantle wedge, serpentinite is present mainly along its basal portion.

all subduction zones, the entrainment may be a common process. Under some conditions, it is possible that buoyant serpentinite may creep updip, so that the effect of the MWC may not be limited to lie all below the Moho. In this section, we propose a model for the effect of mantle wedge serpentinite in our study area as illustrated in Figure 4.

For the P - T conditions relevant to the Maule rupture, the primary serpentine mineral at the MWC is predicted to be mostly lizardite (e.g., Guillot et al., 2015) (Figures 3 and 4), but chrysotile may also be present (Deschamps et al., 2011; Kodolányi et al., 2012). For brevity, we only refer to lizardite in the following discussion while keeping in mind the presence of chrysotile. Lizardite, as well as lizardite + talc mixtures, exhibit velocity-strengthening behavior in rate-state friction experiments under all laboratory conditions (Amiguet et al., 2012; Moore & Lockner, 2011). Rate-state friction applies to low-rate fault slip and therefore governs the initiation of seismic rupture. If this part of the megathrust is dominated by entrained lizardite, it will tend not to initiate earthquakes. If the permeability seal argument of Gao and Wang (2017) is not limited to the warmest subduction zones, the megathrust around the MWC may be under high pore fluid pressure that tends to hinder seismic slip while weakening the fault (Xing et al., 2019). The combination of the two factors may explain the scarcity of interplate aftershocks in this depth range (Figure 2b). However, there is laboratory evidence that lizardite may exhibit mild dynamic weakening at seismic slip rate and therefore allow the propagation of large ruptures (Proctor et al., 2014).

Further downdip, antigorite becomes increasingly abundant as temperature and depth increase (Figures 3 and 4). Various experiments under laboratory hydrothermal conditions indicate that antigorite may promote slip instability at high temperatures. For example, antigorite mixed with a minor amount of talc may exhibit variable degrees of velocity weakening (Moore & Lockner, 2011). Pure antigorite is seen to exhibit unstable (seismic) slip at temperatures over 400°C, presumably associated with heating-induced dehydration and shear localization (Okazaki & Katayama, 2015; Takahashi et al., 2011). The tendency of high- T unstable slip is compatible

with the laboratory observation that antigorite gouge undergoes a ductile-to-brittle transition with increasing temperature under similar P/T conditions (Proctor & Hirth, 2016). There is large uncertainty in extrapolating laboratory results to in situ conditions, but these results qualitatively suggest that antigorite at high enough temperature may facilitate seismic slip some distance downdip of the MWC.

At these P/T conditions, numerous studies indicate that subducted sediment and materials from the subducting crust are mostly velocity-strengthening (see review by Wang & Tréhu, 2016), and so are other hydrous minerals incorporated into the megathrust from the hydrated mantle wedge such as talc (Moore & Lockner, 2008), chlorite (Okamoto et al., 2019), and some metastable lizardite and chrysotile (Mellini et al., 1987). But the presence of antigorite-rich patches embedded in these materials would permit the generation of aftershocks. A very large rupture like in 2010 can propagate through the mostly velocity-strengthening area, facilitated by these patches, but in a sluggish manner retarded by stress increase (Figure 1c). Local stress drop within these patches cannot be resolved by a static slip model (Figure 1).

There is also evidence that high- T antigorite may undergo dynamic weakening via flash heating (Brantut et al., 2016; Hirose & Bystricky, 2007; Kohli et al., 2011; Proctor et al., 2014), although many other rocks and minerals also exhibit weakening at high enough slip rate (Di Toro et al., 2011). We speculate that when the deep fault area slips in a large earthquake, dynamic weakening of these antigorite-rich patches may promote locally fast slip with higher stress drop. This may explain why some of the high-frequency seismic energy is radiated from the area of negative stress drop (Figure 1c). In a study in northern Chile,

Piña-Valdés et al. (2018) found that smaller (down to $M_w = 4$) interplate events also showed a similar tendency of radiating higher-frequency energy from deeper than 40 km, compatible with this speculation.

3.4. Discussion

The overall velocity-strengthening behavior of the fault segment downdip of the MWC in our study area is manifested in afterslip following the Maule earthquake (Bedford et al., 2016; Vigny et al., 2011) as well as the stress increase during the rupture (Figure 1c). It is the afterslip that allows the small antigorite-rich patches in this zone to generate aftershocks. In our conceptual model, these patches are spatially interspersed and may not belong to a single slip surface (Figure 4). In some places, they may be more densely spaced and may interconnect to form a large seismogenic patch. This may be what happened in the 2007 $M_w = 7.7$ Tocopilla megathrust earthquake in northern Chile of which the rupture zone is largely confined to be deeper than 40 km (Schurr et al., 2012).

The Maule aftershock gap stretches quite far along strike (Lange et al., 2012), but a very small segment was bridged by the 2012 $M_w = 7.0$ earthquake (Figure 1a). This event had an initial nucleation phase in the antigorite-rich area (Figure 1a, red star), consistent with the conceptual model outline above, but was followed by a primary phase farther updip through the lizardite-rich area (Figure 1a, blue star) (Ruiz et al., 2013). We speculate that the primary rupture developed as a result of either dynamic triggering by, or dynamic propagation from, the initial rupture. Alternatively, the 2012 rupture might have happened along a slip surface at a different level of the megathrust fault zone, not near the lizardite-rich top. Multiple candidate seismic surfaces are often observed in exhumed ancient megathrust zones (Agard et al., 2018; Rowe et al., 2013).

By conducting the Maule case study, our main purpose is to emphasize the general concept that hydrated materials along the base of the mantle wedge affect megathrust processes. We are mindful of the many uncertainties in the Maule slip distribution, aftershock location, Moho (and thus MWC) definition, mineral assemblage in the mantle wedge and megathrust zone, serpentine phase relations, extrapolation of laboratory fiction results to in situ conditions, and so forth. Our proposed mechanism awaits further testing in future research that can reduce these uncertainties.

A number of factors need to be taken into consideration when extrapolating the concept to other subduction zones. The specific reactions and minerals shown in Figure 3 may not apply to places with different P/T conditions, Moho depths, and/or abundance of other hydrous minerals, especially talc (Moore & Lockner, 2008, 2011) and chlorite (Okamoto et al., 2019). Because of compositional and structural heterogeneities of the fault zone and variable P/T conditions, the process may differ even in different places along the same subduction zone. Depending on the fracture-controlled alteration state of the subducting plate, fluid supply is expected to vary along strike, giving rise to variable degrees of mantle wedge serpentinization that influence megathrust behavior differently. Furthermore, the mantle wedge material may not always overshadow the effects of other fault zone materials (Figure 4) in controlling the megathrust seismogenic behavior.

4. Conclusions

A synthesis of published rupture models of the 2010 $M_w = 8.8$ Maule, Chile, earthquake suggests that coseismic slip extended to at least 55 km depth, with stress drop occurring mostly updip of the 32–40 km MWC depth. Interplate aftershocks extended much deeper than the MWC but showed a clear gap around the MWC. We propose that the slip and aftershock patterns may be controlled by serpentinites derived from the base of the mantle wedge that are entrained in the megathrust fault zone. The main points of the conceptual model are as follows.

1. Based on results from our thermal modeling and serpentine stability conditions from the literature, we infer that in the Maule region the megathrust contains abundant lizardite and chrysotile around the MWC and abundant antigorite farther downdip. In addition to serpentine minerals, hydrated ultramafic regions within the megathrust shear zone will contain additional hydrous minerals such as chlorite and talc.
2. The velocity-strengthening behavior of lizardite/chrysotile may contribute to the paucity of aftershocks around the MWC. Unstable slip of antigorite-rich patches may lead to aftershocks farther downdip.

3. The megathrust downdip of the MWC is predominantly velocity strengthening but allows the propagation of large ruptures. Antigorite-rich patches may have radiated high-frequency energy during coseismic slip of the Maule earthquake.

Data Availability Statement

No new data are used in this work. Aftershock data displayed in Figures 1a and 2 are available through Lange et al. (2012). Energy peak locations displayed in Figures 1c are available through Palo et al. (2014).

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