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# Megathrust friction determined from mechanical analysis of the forearc in the Maule earthquake area



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### ABSTRACT

The seismogenic potential of a given fault depends essentially on its frictional properties and on the mechanical properties of the medium. Determining the spatio-temporal variations of frictional properties is therefore a key issue in seismotectonics. This study aims to characterize the friction on the South America megathrust in the 2010 Mw 8.8 Maule earthquake area from mechanical analysis of the forearc structure and morphology. Based on the critical taper theory, we first show that the rupture area of the Maule earthquake, also shown to be locked in the interseismic period, coincides with the stable part of the wedge. In the surrounding area, the wedge is critical, a finding consistent with various evidence for active deformation there. This is in particular true for the Arauco Peninsula area which seems to have arrested the Maule earthquake's rupture to the South. This observation lends support to the view that the seismic rupture is inhibited when propagating beneath a critical area. The geometry of the critical portion of the wedge suggests a standard internal friction ( $\mu_{int} = 0.7 \pm 0.13$ ) and a hydrostatic pore pressure within the wedge. The effective friction beneath the critical outer wedge is estimated to be  $\mu_{eff}^{eff} = 0.27 \pm 0.03$ . This could be related to intrinsically low friction minerals (clay) or high pore pressure along the megathrust. We next use the limit analysis approach to constrain the variation of the effective friction along the megathrust based on the location and geometry of internal faulting within the forearc. A low effective friction is found within the rupture area ( $\mu_b^{eff} \leq 0.14$ ) to explain the reactivation of thrust fault such as the Santa Maria, updip of the coseismic rupture, or the activation of normal splay faults downdip of the rupture area. The low effective friction found there could reflect strong dynamic weakening.

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# 1. Introduction

The determination of the mechanical properties of subduction megathrusts and forearcs is an important goal of seismotectonics for a number of reasons. First, these properties determine the mechanical coupling across the subduction zone and, as such, are thought to influence state of stress, elevation and deformation style of the continental margin (e.g., Hassani et al., 1997; Bonnardot et al., 2008; Lamb and Davis, 2003). Second, the factors that determine the seismic potential of a subduction megathrust remain poorly understood and there are hints that the structure and mechanical state of the forearc might provide some insight. In particular, the shallower, presumably rate-strengthening portion of the outer accretionary prism, the most frontal part of the forearc formed of imbricated thrust sheets of accreted sediments, which

\* Corresponding author. *E-mail address:* cubas@caltech.edu (N. Cubas). is considered to deform internally (Byrne et al., 1987; Ruff and Tichelaar, 1996; Fuller et al., 2006; Wang and Hu, 2006). The limit between the deforming wedge and the more internal stable part of the wedge would then mark the updip portion of the seismogenic zone as suggested from the correlation between the rupture extent of large megathrust earthquakes with shelf-terraces or forearc basins marked by local gravity lows (Song and Simons, 2003; Wells et al., 2003). Splay faults are commonly observed at the backstop of the deforming wedge and their location seem to mark the updip limit of megathrust ruptures (Collot et al., 2008). The fact that splay faults form at the transition between aseismic and seismic patches has also been observed in analog experiments (Rosenau and Oncken, 2009). As the morphology of the deforming accretionary prism naturally evolves toward a critical geometry determined by the friction along the megathrust and the wedge strength (Davis et al., 1983), the frictional properties could then control both the seismogenic behavior and the forearc morphologv.

In this study, we analyze the forearc structure and morphology in the area of the 27th February 2010 Mw 8.8 Maule earthquake

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Fig. 1. (a) Coseismic slip model of the 2010 Mw 8.8 Maule earthquake obtained by Lin et al. (2013) from inversion of geodetic, seismic and tsunami data, and slip model for the northern rupture of the 1960 Mw 9.5 Valdivía earthquake from Moreno et al. (2010) in green. Large red stars: locations of hypocenters, small blue stars: Pichilemu normal aftershocks. Surface evidence of the Pichilemu sequence are reported in blue. (b) Morpho-structural map of South Central Chile (based on Melnick and Echtler, 2010; Melnick et al., 2006, 2009; Geersen et al., 2011; Farías et al., 2011; Schobbenhaus and Bellizzia, 2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to place constraints on the frictional properties of the megathrust. In the following section, we review the characteristics and the seismotectonic setting of the study area. We assess next a possible correlation between the spatial variations of the frictional properties and the mode of slip along the megathrust. To constrain the frictional properties, two different approaches are used. The first one, presented in Section 3, relies on the critical taper theory (Davis et al., 1983; Dahlen, 1984). The second approach, applied to the deeper locked section is presented in Section 4 and relies on the limit analysis theory (Salençon, 2002; Maillot and Leroy, 2006). It is used to retrieve spatial variations of effective basal friction required to explain the location of some documented splays faults.

# 2. Seismotectonic setting and characteristics of Maule earthquake

The Maule earthquake ruptured the Concepción segment (33°S-38°S) of the South America megathrust which accommodates the 65–85 mm/a convergence between the Nazca and South America plates (DeMets et al., 1994; Angermann et al., 1999) (Fig. 1). Prior to 2010, it had last ruptured in 1835 and therefore had been identified as a seismic gap (Campos et al., 2002; Ruegg et al., 2009; Madariaga et al., 2010). A number of coseismic slip models of the Mw 8.8 Maule earthquake have been derived (Lin et al., 2013; Delouis et al., 2010; Lorito et al., 2011; Vigny et al., 2011). Although they vary regarding the details, most of them are quite similar to first order. In this study, we refer to the particular coseismic model of Lin et al. (2013) which was derived from seismological, GPS, inSAR and tsunami data (Fig. 1a). Geodetic strain measured before the earthquake shows that the 80 km × 350 km rupture area coincides with a portion of the plate interface that had remained strongly locked (Moreno et al., 2010; Métois et al., 2012). As indicated from the relatively modest tsunami, the rupture didn't reach the trench (Lorito et al., 2011; Lin et al., 2013). The down-dip extent of the rupture follows the coastline as often observed for large megathrust earthquakes along the South America subduction zones (Ruff and Tichelaar, 1996; Sladen et al., 2010). The southern end of the rupture coincides with the Arauco Peninsula (Fig. 1b), an anomalous trench-coast distance and relief feature, which is known to have also acted as a barrier for past earthquakes (Lomnitz, 1970; Kaizuka et al., 1973; Melnick et al., 2009; Contreras-Reyes and Carrizo, 2011).

The mainshock induced aftershocks including a number of events with a thrust mechanism on the plate interface in the area surrounding and adjacent to the coseismic rupture (Rietbrock et al., 2012). Evidence for activation of forearc structures was also observed. These include normal faults near the town of Pichilemu which produced a major sequence of shallow aftershocks with two major events of magnitude Mw = 6.9 and 7.0 (Ryder et al., 2012; Farías et al., 2011) (Fig. 1a). The seismicity delineates an NW trend, consistent with the location and orientation of secondary surface cracks (Farías et al., 2011), and shows an SW dip between 40 and 83° from the surface down to the interplate (Fig. 1a). Evidence of activation of thrust faulting within the forearc was found on the Santa Maria island (Fig. 1b). The elevated topography of the island itself was formed as a result of thrusting along a 72°W dipping backthrust fault which most probably roots at depth into the



Fig. 2. Structural profiles from cross-sections AA' and BB' of Fig. 1b, modified from Melnick et al. (2006) and Geersen et al. (2011).

megathrust (Fig. 2, top) as highlighted by the seismicity recorded before the 2010 earthquake (Melnick et al., 2006). This backthrust fault has been interpreted as an inverted Early Pliocene normal fault related to the rift structure of the Arauco shelf basin (Melnick et al., 2006). The island has been the focus of previous studies because of repeated earthquake-related uplift. Melnick et al. (2012) reported a 1.6 m uplift during the 2010 earthquake, Darwin (1851) measured 2.4 m to 3 m of uplift two and six weeks after the 1835 M > 8 earthquake (Lomnitz, 1970), while Melnick et al. (2006) estimated a 6 m uplift related to the 1751 M > 8 event. The island is located close to the updip limit of the coseismic rupture (Fig. 1a). The splay fault may have been activated during or after the mainshock.

There is additional geological evidence for active deformation of the forearc at various other places offshore and onshore. Some splay faults are documented from geophysical investigations within the accretionary prism (Melnick et al., 2006, 2009; Geersen et al., 2011). These thrust faults are clear indication that the outer wedge is in critical state in the sense of the critical taper theory (Fig. 2). Both the Nahuelbuta range and the Arauco Peninsula are actively deforming as suggested from their relief and uplift documented from raised shorelines and thermochronology (Melnick et al., 2009). The relief of the Nahuelbuta Range is twice the relief of the coastal cordillera, and its exhumation rate has been estimated to be 0.03–0.04 mm/a until 4  $\pm$  1.2 Ma, with an increase to <0.2 mm/a since that time (Glodny et al., 2008). At the Arauco Peninsula, the maximum uplift rate obtained is  $1.8 \pm 0.4$  mm/a over the past 50 ka (Melnick et al., 2006) and 2.3  $\pm$  0.2 mm/a over the past 3 ka (Bookhagen et al., 2006). In the following section we use the information on the morphology, structure and deformation of the forearc to constrain its mechanical state and friction along the megathrust. We assume that the state of stress of the forearc wedge above the megathrust is limited by its brittle strength and analyze the implications for the stress level along the megathrust. The analyzed domain extends from the trench to the Nahuelbuta range. The analysis provides an estimate of the quasistatic stresses within the wedge and along the megathrust needed to bring the wedge to the verge of brittle failure. Deformation in the deeper area, where the megathrust reaches a depth of about 50 km, might in fact be ductile. The analysis still provides some insight but the inferred basal friction might then be seen as an effective basal friction, a proxy for viscous stress. However we believe that this area is still dominantly in the brittle domain based on the relatively low temperature estimated from thermokinematic modeling (less than 400 °C according to Völker et al., 2011), the distribution of aftershocks (Rietbrock et al., 2012) and the time-evolution of afterslip which suggests a brittle creep mechanism (Lin et al., 2013).

#### 3. Constraints derived based on the critical taper theory

The Coulomb wedge theory considers the mechanics of an accretionary wedge as analogous to sand pushed by a moving bulldozer along a frictional décollement (Davis et al., 1983). The wedge evolves into a critical geometry, corresponding to a point of internal state of stress for which the whole wedge including the basal décollement is on the verge of Coulomb failure. If the décollement is planar and material properties are homogeneous, the critical wedge is triangular for a cohesionless wedge. The conditions for stress equilibrium, Coulomb yielding of the wedge and frictional sliding along its base have an analytical solution. In fact



Fig. 3. (a) Initial and smoothed topography and slab morphology of the AA' cross-section of Fig. 1b. (b) Topographic slope and slab dip of the cross-section AA' compared to 3 different critical envelopes for an internal angle of friction of 30°, two different pore pressure, one hydrostatic ( $\lambda = 0.4$ ), one high ( $\lambda = 0.8$ ) and two different angles of effective basal friction (5° and 10°).

two critical states can be defined: one in which the wedge is on the verge of failure in horizontal compression and another in which the wedge is on the verge of failure in horizontal extension. In this study, we use the solution for a cohesionless wedge established by Dahlen (1984) and generalized with a Mohr's construction by Lehner (1986). The critical taper angle is a function of the angle  $\Psi_{B}$  formed by the maximum principal stress  $\sigma 1$  and the base of the wedge, and the angle  $\Psi_0$  formed by  $\sigma 1$  and the top of the wedge. The solution corresponding to the compressional branch is:

$$(\alpha + \beta)_c = \Psi_B - \Psi_0, \tag{1}$$

where the subscript c means critical and the two angles  $\Psi_B$  and  $\Psi_0$  are

$$\Psi_B = \frac{1}{2} \arcsin\left(\frac{\sin\phi'_b}{\sin\phi_b}\right) - \frac{1}{2}\phi'_b,\tag{2}$$

$$\Psi_0 = \frac{1}{2} \arcsin\left(\frac{\sin\alpha'}{\sin\phi_{int}}\right) - \frac{1}{2}\alpha'.$$
(3)

The angles  $\phi_{int}$  and  $\phi_b$  are the internal and basal angles of friction. They are defined as:

 $\mu_{int} = \tan \phi_{int},$ 

 $\mu_b = \tan \phi_b.$ 

The two angles  $\phi'_h$  and  $\alpha'$  introduced in (2) and (3) are such that

$$\tan \phi_b' = \left(\frac{1 - \lambda_b}{1 - \lambda}\right) \tan \phi_b,\tag{4}$$

$$\alpha' = \arctan\left[\left(\frac{1-\rho_w/\rho}{1-\lambda}\right)\tan\alpha\right].$$
(5)

They account for the pore fluid pressure through the generalized internal and basal Hubbert–Rubbey fluid pressure ratios  $\lambda$  and  $\lambda_h$ :

$$\lambda = \frac{P + \rho_w g D}{|\sigma_z| + \rho_w g D},$$
  

$$\lambda_b = \frac{P_b + \rho_w g D}{|\sigma_z| + \rho_w g D},$$
(6)

with  $\rho$  and  $\rho_w$  being the densities of the wedge material and pore fluid (water), *D* the water depth and  $\sigma_z$  the vertical stress. As shown by Wang et al. (2006), the solution is exact if  $\lambda = \lambda_h$ , otherwise it is a valid approximation if a small taper is assumed. The reader is referred to Lehner (1986) for the full equations. For the sake of clarity, we define an effective basal friction as  $\mu_b^{eff} = \tan \phi_b^{eff} = (1 - \lambda_b) \tan \phi_b.$ The theoretical relation (1) between  $\alpha$  and  $\beta$  forms a critical

envelope defining three different mechanical states (Fig. 3b):

- (1) a critical state, the wedge is on the verge of failure everywhere, in horizontal compression along the lower branch and in horizontal tension along the upper branch of the envelope.
- (2) a stable state, if the taper angle lies in between the envelope limits. The wedge is mechanically stable and can slide along the décollement without any internal deformation.

**Fig. 4.** Upper and lower bound of acceptable effective basal friction, as a function of the internal friction for different Hubbert and Rubbey parameter  $\lambda$  (Fig. 4) for the Maule segment (a), the Arauco Peninsula (b) and the Northern Valdivía segment (c). Cross-sections variability is represented in light gray for the upper bound, in dark gray for the lower bound. The thick black lines are the means.

(3) unstable state, if the taper lies outside the envelope. The Coulomb yielding limit on the strength of the wedge implies that the taper angle of a wedge in quasistatic equilibrium cannot be lower than the critical taper in compression nor higher than the critical taper in extension; a wedge lying in the area outside the envelope is therefore unstable.

As shown in the appendix, the critical taper theory holds for a curved megathrust as long as its radius of curvature is large compared to the wedge thickness.

The observed topographic slope and dip angle of the megathrust are consequently used to place constraints on the model parameters. The  $\alpha$ - $\beta$  curve describing the geometry of the forearc must lie within the area defined by the critical envelope as in the cross-section AA' (Fig. 1b) in Fig. 3. A given portion of the forearc can either be in the stable domain or in a critical state, in which case some evidence for internal deformation of the wedge would be expected. The topographic slope and the slab dip along sections across the south central Chilean forearc are thus used to determine the range of possible values of the model parameters so that the wedge is everywhere stable or in a critical state. We analyzed 300 km long profiles. To determine the topographic slope  $\alpha$ , we used ETOPO1 (Amante and Eakins, 2009, resolution 1'). To filter out the high-frequency content, the topographic profiles were smoothed using a sliding window. Different smoothing functions (triangular and rectangular) and width (10, 25 and 40 km) were tested. The reader is referred to the appendix for the discussion of the details and presentation of these tests. Only the results obtained with the topography smoothed by a 25 km wide rectangular window are shown here. The slab geometry is extracted from the slab 1.0 model of Hayes et al. (2012) which is based on a large compilation of data from active source, passive seismology and position of trenches (resolution  $0.02^{\circ}$ ).

We distinguish three different areas: the northern one corresponds to the 2010 Mw 8.8 Maule earthquake rupture, the central one to the Arauco Peninsula area, and the southern one to the northern part of the 1960 Mw 9.5 Valdivía earthquake rupture (Fig. 1a). For each area, the upper (compression) and lower (extension) bound of acceptable effective basal friction angles as a function of the internal friction angle assuming different internal pore pressure ratios are determined (Fig. 4).

The three areas show a similar range of acceptable parameters. For an angle of internal friction of  $\phi_{int} = 35^{\circ}$  ( $\mu_{int} = 0.7$ ) and a hy-

drostatic fluid pore pressure ratio ( $\lambda = 0.4$ ), the angle of effective basal friction has to be  $1^{\circ} \leq \phi_b^{eff} \leq 16^{\circ}$  ( $0.017 \leq \mu_b^{eff} \leq 0.286$ ). For a very high internal pore pressure ratio ( $\lambda > 0.8$ ), the acceptable range narrows down to:  $1^{\circ} \leq \phi_b^{eff} \leq 5^{\circ}$  ( $0.017 \leq \mu_b^{eff} \leq 0.08$ ). This analysis shows that the basal effective friction must be relatively low, less than about  $17^{\circ}$  ( $\mu_b^{eff} < 0.3$ ) if a standard value of the internal friction angle ( $30-40^{\circ}$ ) and a hydrostatic pore pressure ratio are assumed ( $\lambda = 0.4$ ).

Tighter constraints can be determined from the measured taper angle on those areas which are known to be in a critical state based on evidence of forearc deformation reviewed in the previous section. For this analysis, we considered five domains including three covering the rupture area of the Maule earthquake to capture the major lateral variations of the morphology of the forearc (Fig. 5). We computed an average swath profile for each domain (individual profiles are shown in the supplementary material, Fig. S1). Inspection of profiles show that some portions seem to follow the approximately linear relationship between  $\alpha$  and  $\beta$ defining the critical state (Fig. 5b). This is particularly true for the outer wedge where there is evidence for internal thrust faulting (Fig. 2). In the Arauco Peninsula area, the wedge seems to follow the critical state envelope from the trench to the crest of the peninsula. Another portion of the profile, farther inland corresponding to the Nahuelbuta Range, also seems to follow a critical envelope that would then require a higher basal friction.

We then mapped the zones which are presumably critical by assessing the probability that a given portion of an individual profile follows a critical envelope. In practice, we evaluate this probability based on the local linearity of the  $\alpha$ - $\beta$  curve (see the appendix). The two critical zones in the Arauco Peninsula area appear to be separated by a relative narrow stable zone.

The Valdivía segment shows some significant variability along strike, but a critical section at the front nonetheless shows up in the swath profile. A limited zone inland is possibly at criticality at the southern edge of the study area. This zone would start at the coastline.

The southernmost profile in the Maule rupture area (Fig. 2, top), shows also that the outer wedge is critical from the trench up to the edge of the continental shelf. A second narrower critical area seems to show up further inland, starting also at the coastline. These critical zones lie in the continuity of those identified within the Arauco Peninsula area, though the intervening stable area is broader.





**Fig. 5.** (a) Areas at critical mechanical state are represented in red, the rest of the forearc is mechanically stable. (b) Tapers of each segment along the trench. Black: mean of the segment, gray: mean  $\pm \sigma$ . Critical sections are in orange for the accretionary prism, in red for the inner wedge, in dark red for the coastal cordillera. Dash-dotted lines are theoretical critical envelopes for increasing effective basal friction from  $\phi_b^{eff} = 16$  to 22° ( $\mu_b^{eff} = 0.28-0.4$ ) with an internal friction angle of 35° ( $\mu = 0.7$ ) and a hydrostatic pore fluid pressure  $\lambda = 0.4$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Two main critical regions are thus revealed by this analysis:

- one at the frontal part of the forearc mainly corresponding to the accretionary prism, with wider regions in the northern part of the Maule segment, and at the Arauco Peninsula,
- some portions of the Coastal Cordillera, such as the northern part of the Maule segment, the Arauco Peninsula and the Nahuelbuta range East of the peninsula, and the southern cordillera of the Valdivía segment.
- All other areas are mechanically stable.

Now that the presumably critical areas are identified, we proceed to retrieve the corresponding best-fitting model parameters. To do so, we first computed a mean and standard deviation for each critical zone (Fig. 5b). We assume a density of 2800 kg/m<sup>3</sup> and calculate the predicted dip angle of the megathrust,  $\beta^{calc}$ , based on the critical taper theory given the observed topographic slope  $\alpha$ . There are three model parameters: the internal friction

angle  $\phi_{int}$ , the effective basal friction angle  $\phi_b^{eff}$  and the internal pore fluid ratio  $\lambda$ . We evaluate the merit of each set of model parameters by comparing the predicted,  $\beta^{calc}$  (Eq. (1)), and observed,  $\beta^{obs}$ , values of the taper angle with an L2 norm (assuming a Gaussian distribution of errors). The uncertainty on the taper angle is  $\sigma = \sigma_{\beta_{obs}} + \sigma_{\alpha}$  including the contribution of the uncertainties on the topographic slope,  $\sigma_{\alpha_{obs}}$  and dip angle  $\sigma_{\beta_{obs}}$  on the predicted taper angle. The misfit *M* function calculated for each point of the sampling  $(n\beta)$  is then:

$$M_{\beta} = \frac{1}{n\beta + 1} \sum_{i=1}^{n\beta} \frac{1}{2} \frac{(\beta^{obs}(i) - \beta^{cal}(i))^2}{(\sigma(i))^2}.$$
 (7)

The probability density distribution of the model parameters is computed based on the misfit, following Tarantola (2005):

$$P(\phi_{int}, \phi_b^{eff}, \lambda) = \frac{1}{K} e^{-M(\phi_{int}, \phi_b^{eff}, \lambda)},$$
(8)



**Fig. 6.** Marginal 1D probability distributions for the three Maule segments (North, Central and South), the Arauco Peninsula (AP) segment and the Valdivía segment.  $\phi_{int}$  the internal friction,  $\lambda$  the internal pore fluid ratio,  $\phi_b^{eff}$  the effective basal friction. Results in orange for the accretionary prism, in red for the inner wedge and in dark red for the coastal cordillera. Best fits represented by circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with K the constant normalization factor of the probability over the model space:

$$K = \int_{\phi_{int}} \int_{\phi_{b}^{eff}} \int_{\lambda} e^{-M(\phi_{int}, \phi_{b}^{eff}, \lambda)} d\phi_{int} d\phi_{b}^{eff} d\lambda.$$
(9)

Since the probability density has three dimensions, to visualize the results, 1D marginal probabilities are calculated from integrations over two model space parameters. These marginal probabilities provide the distributions of one parameter independently of others, also named 1D marginal probability density (Fig. 6), for instance for  $\phi_{int}$ :

$$P(\phi_{int}) = \int_{\phi_b^{eff}} \int_{\lambda} P(\phi_{int}, \phi_b^{eff}, \lambda) d\phi_b^{eff} d\lambda.$$
(10)

The pore fluid pressure ratio is loosely constrained but consistently shows a most likely value close to hydrostatic ( $\lambda = 0.4$ ). The probability distribution function of the internal friction peaks between 40 and 45° ( $\mu_{int} = 0.83$  to 1), with 68% of probability of being in the range of 25 to 50° ( $\mu_{int} = 0.44$  to 1.19) with slightly lower values below the Nahuelbuta range (35°,  $\mu_{int} = 0.7$ ). For the Valdivía area, the effective basal friction of the accretionary prism shows low values with peaks at about 7 to 8° ( $\mu_b^{eff} = 0.12$  to 0.14). The Arauco Peninsula accretionary wedge yields somewhat higher values (12°,  $\mu_b^{eff} = 0.21$ ), and the effective basal friction increases again beneath the Nahuelbuta range (16°,  $\mu_b^{eff} = 0.28$ ). For the Maule segment, the effective basal friction beneath the outer wedge peaks at 11–15°,  $\mu_b^{eff} = 0.19–0.26$ . The central Maule segment shows strong morphological variations, inversion results are

thus poorly constrained. The same applies for the coastal cordillera of the Maule and Valdivía segments. Best fitting values are reported in Table 1. As the basal pore pressure is most likely equal or higher than the internal one, basal frictions were reported for the case  $\lambda_b = \lambda$ , providing a lower bound on the basal friction angle. The values of  $\phi_{int}$  and  $\lambda$  obtained from this analysis are mostly reasonable. For comparison, laboratory measurements of internal friction angles for most common quartzo-feldspathic rocks are generally in the range of 0.6 to 0.85 (Byerlee, 1978). By contrast, the value of the effective basal friction is low and could point to either dominantly low friction minerals along the megathrust or high pore pressure.

In a second step, to limit the trade-off among the model parameters, we run partial inversion fixing either the internal friction to a standard value ( $\phi_{int} = 35^{\circ}$ ) or the internal pore pressure ratio parameter to hydrostatic ( $\lambda = 0.4$ ) (Fig. 7). From the probability distribution as well as the best fit results reported in the supplementary material, Tables SM 2-1 and SM 2-2, the internal friction appears to be constrained to a narrower range, between 26 and 35°, and the pore pressure ratio is confirmed to be hydrostatic excepted along the accretionary prism of the Valdivía segment where larger values are required. In order to provide a view of the spatial variations of the frictional properties, the best fitting effective basal friction of each section has been reported in Fig. 9.

The effective basal friction is quite homogeneous in the accretionary prism of the Arauco and Maule segments with values ranging between 14 and 17.5° ( $\mu_b^{e\!f\!f} = 0.25 - 0.31$ ). It appears larger below the Nahuelbuta range at 21.25° ( $\mu_b^{e\!f\!f} = 0.39$ ) and lower in the accretionary prism along the Valdivía segment ( $\phi_b^{e\!f\!f} = 6^\circ$ ,  $\mu_b^{e\!f\!f} = 0.1$ ). We show in the appendix that the analysis is robust despite the large uncertainty on the megathrust geometry.

Table 1	
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Best misfit for each segment.

Segment	λ	<i>φ<sub>int</sub></i> (°)	$\mu_{\mathit{int}}$	$\phi^{e\!f\!f}_b$ (°)	$\mu_b^{e\!f\!f}$	$\begin{array}{l} \phi_b \\ \text{if } \lambda_b = \lambda \end{array}$	
Maule North							
accretionary prism	0.60	40.75	0.86	16.25	0.29	36	0.72
inner wedge	0.65	43.75	0.95	17.5	0.31	41.5	0.88
Maule South							
accretionary prism	0.55	37.0	0.75	15.75	0.28	32.9	0.62
inner wedge	0.525	37.75	0.77	17.5	0.31	33	0.65
Arauco Peninsula							
accretionary prism	0.375	29.25	0.56	14.25	0.25	22	0.4
inner wedge	0.375	31.5	0.61	16.0	0.28	24	0.45
coastal cordillera	0.475	38.5	0.79	21.25	0.39	36.6	0.74
Valdivía							
accretionary prism	0.7	25.75	0.48	6.25	0.11	20	0.36



**Fig. 7.** Marginal 1D probability distributions of (a)  $\phi_{int}$  and  $\phi_b^{eff}$  with  $\lambda = 0.4$ , (b)  $\phi_b^{eff}$  and  $\lambda$  with  $\phi_{int} = 35^\circ$ . Results in orange for the accretionary prism, in red for the inner wedge and in dark red for the coastal cordillera. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

# 4. Spatial variations of frictional properties deduced from the limit analysis

Here we use the information available on the geometry and location of some splay faults to bring additional constraints on the frictional properties along the megathrust. To do so, we now apply the limit analysis approach (Chandrasekharaiah and Debnath, 1994; Salencon, 2002). This approach is based on the principle of virtual powers and the theorem of maximum rock strength (Maillot and Leroy, 2006). In this study, the Coulomb criterion is used to define the maximum rock strength. The method investigates all possible collapse mechanisms as a function of the frictional properties and selects the optimal one leading to the least upper bound to the tectonic force. The advantages compared with the critical taper theory are that there is no need to assume homogeneous mechanical properties nor that the wedge be at critical state. This method has previously been applied to retrieve frictions along the Nankai accretionary prism (Cubas et al., 2008; Souloumiac et al., 2009; Pons et al., 2013) and validated by comparison with analogue sandbox experiments (Cubas et al., 2013). The analysis is analytical for simple geometries and numerical otherwise. The procedure presented by Souloumiac et al. (2010) is applied here.

As a test example meant to develop some intuition of the model prediction, we ran some simulations in which we assume a planar megathrust and a constant taper angle (Fig. 8 a to c). We assume three segments with different but uniform basal friction along each. We choose an initial geometry so that the wedge is stable but close to critical in horizontal compression. The explored kinematics correspond to sliding along the full length of a portion of the megathrust with or without internal faulting within the wedge. Fully activated megathrust implies the formation of splay faults at the transition between the segments of different frictions. In the case of an increase of friction towards the trench, a backthrust forms at the transition (Fig. 8a), whereas a decrease of friction leads to the formation of a forethrust (Fig. 8b). A strong decrease can even lead to the formation of a normal fault (Fig. 8c). Virtual velocities (Chandrasekharaiah and Debnath, 1994; Salençon, 2002) are provided in the supplementary material (Fig. S3). Pons and Leroy (2012) studied the same prototype with two distinct regions on the megathrust and confirmed by analytical means that transition of frictions could lead to the formation of splay faults.



**Fig. 8.** Distance to the Coulomb criterion (red: far from the rupture, blue: at the rupture) for (a) an increase of effective basal friction towards the toe, (b) a decrease of basal friction towards the toe, (c) a very strong decrease, for a wedge of 200 km long, transitions at 60 and 120 km, with a topographic slope  $\alpha = 3^{\circ}$  and a décollement dip  $\beta = 6^{\circ}$ , internal friction of 30°, (d) the Santa Maria backthrust set-up with  $\phi_{int}^{eff} = 21^{\circ}$ , (e) the Pichilemu normal fault with  $\phi_{int}^{eff} = 18.5^{\circ}$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We start with the modeling of the Santa Maria backthrust splay fault (Fig. 8d). Since the fault is thought to be a pre-existing reactivated normal fault, the fault geometry is prescribed based on the geometry derived from structural and geophysical observations (Melnick et al., 2006). Since the variations of the topographic and basal slopes are small compared to the wedge thickness, we simplify the geometry by assuming a constant megathrust dip angle ( $\beta = 13.5^{\circ}$ ) and two different topographic slopes, one for the outer wedge ( $\alpha_1 = 1.7^{\circ}$ ) another for the Arauco shelf basin ( $\alpha_2 = 0^{\circ}$ ). The modeled megathrust is 104 km long.

The internal friction and updip basal friction are imposed to the values derived from the critical taper analysis. The effective inter-nal friction is set at  $\phi_{int}^{eff} = 21^{\circ}$  ( $\mu_{int}^{eff} = 0.383$ , for  $\phi_{int} = 31.5^{\circ}$  and  $\lambda = 0.375$ ). We then seek the effective basal friction within the seismogenic zone and the backthrust effective friction that will activate the fault. In order to activate the backthrust, the friction along this fault has to be equal or larger than  $\phi_f^{e\!f\!f} \ge 10^\circ$ ( $\mu_f^{e\!f\!f} \ge 0.17$ ). Some secondary shear zone rooting into the backthrust are systematically observed. It is due to the fact that the backthrust is not optimally oriented, leading to secondary faults alike those featured in the structural section of Melnick et al. (2006). For  $\phi_{aseis}^{eff} = 16^{\circ}$  ( $\mu_{aseis}^{eff} = 0.28$ ) along the updip aseismic portion of the megathrust found with the critical taper theory, activation of the splay fault requires the effective basal friction in the seismogenic zone to be lower or equal to  $\phi_{seis}^{eff} = 12^{\circ}$  ( $\mu_{seis}^{eff} = 0.21$ ). For slightly lower  $\phi_{aseis}^{eff} = 14^{\circ}$ , the geometry of the secondary back-thrust matches between the characteristic Activities of the set of the secondary backthrust matches better the observations. Activation of the splay fault then requires the effective basal friction in the seismogenic zone to be lower or equal to  $\phi_{seis}^{eff} \leq 10^{\circ}$  ( $\mu_{seis}^{eff} \leq 0.17$ ). The limit analysis approach provides virtual velocities along each segment of faults. The ratio between the virtual velocities of two segments projected along their fault is assumed to be equal to the ratio of actual displacement between those segments. We find that to get about the right proportion between the vertical throw on the Santa Maria backthrust (1.6 m, Melnick et al., 2012) and the slip along the seismogenic zone below the island (6 m, Lin et al., 2013), for a  $\phi_{aseis}^{eff} = 14^{\circ} \ (\mu_{aseis}^{eff} = 0.25)$ , the seismogenic effective friction has to be  $\phi_{seis}^{eff} < 4^{\circ} \ (\mu_{seis}^{eff} < 0.07)$ . The same analysis is now applied to the normal fault activated

The same analysis is now applied to the normal fault activated by the Pichilemu aftershock sequence which started two weeks after the Maule earthquake (Ryder et al., 2012; Farías et al., 2011). We consider a pre-existent fault striking 70°E (Fig. 8e). The décollement dip angle is set to  $\beta = 19^{\circ}$  and two different topographic slopes were considered, one for the coastal area ( $\alpha_1 = 0^{\circ}$ ) another for the shelf basin ( $\alpha_2 = 1.5^{\circ}$ ) along a 120 km long wedge.

Based on the critical taper results for the inner wedge, the effective internal friction is set to  $\phi_{int}^{eff} = 18.5^{\circ}$  ( $\mu_{int}^{eff} = 0.344$ , for  $\phi_{int} = 43.75^{\circ}$ ,  $\lambda = 0.65$ ) and the down-dip basal friction is chosen so that the wedge is close to critical state in horizontal compression with  $\phi_{aseis}^{eff} = 14^{\circ}$  ( $\mu_{aseis}^{eff} = 0.25$ ). To obtain normal motion on the fault, the seismogenic effective basal friction has to be lower or equal to  $\phi_{seis}^{eff} \leq 8^{\circ}$  (for  $\phi_{aseis}^{eff} \leq 0.14$ ) and the friction along the fault  $\phi_f^{eff} \leq 9^{\circ}$ . No associated deformation is observed.

This analysis is based on a quasistatic force balance and we do not take into account possible dynamic branching. The deformation of the Santa Maria backthrust fault is permanent and recurrent and the Pichilemu aftershock sequence occurs two weeks after the main event. Thus, activation of these splay faults has most probably resulted from a static stress change, justifying our static stress equilibrium analysis.

#### 5. Discussion/conclusion

We now discuss how the mechanical state of the forearc and the inferred frictional properties compare with the coseismic rupture, afterslip and interseismic locking of the megathrust. We use the coseismic slip and afterslip models obtained by Lin et al. (2013), from the joint inversion of geodetic, seismic, and tsunamic data (Fig. 9a). We also refer to the coseismic slip of the 1960 Mw 9.5 Valdivía earthquake of Moreno et al. (2010) (Fig. 9a) and the interseismic strain accumulation model of Métois et al. (2012) (Fig. 9b).

A striking result is that the rupture area of the Maule earthquake, and possibly of the 1960 Valdivía earthquake coincides with stable areas of the forearc and is surrounded with critical areas. The updip limit of the 2010 rupture coincide well with the maximal extent of the critical outer wedge. The coseismic slip due to the 1960 rupture seems to taper down quite abruptly beneath the critical outer wedge. We also observe that most of the wedge forearc seems critical in the Arauco Peninsula which separates the 1960 and 2010 ruptures, and in the area just North of the 2010 rupture. The few critical patches along the coastal cordillera also delimit the down-dip extent of the coseismic slip. Similarly, we observe that the megathrust beneath the stable areas of the forearc wedge was mostly locked in the interseismic period (Fig. 9b).



Fig. 9. Comparison of critical areas in red with (a) Maule earthquake coseismic and postseismic slip models from Lin et al. (2013) and Valdivía earthquake coseismic slip model from Moreno et al. (2010) with (b) interseismic strain accumulation model from Métois et al. (2012). (c) Effective basal friction map based on critical taper and limit analysis results, hatching: extrapolation of results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The comparison with the afterslip distribution is also instructing. Aseismic afterslip is observed downdip of the seismic rupture. below the Nahuelbuta range and seaward of the Arauco Peninsula (Lin et al., 2013). The critical areas appear thus to surround the seismic rupture and to be correlated with areas of postseismic sliding. These observations support the claim that the propagation of a megathrust seismic rupture is probably inhibited where the hanging wall is in critical mechanical state, in particular beneath the outer wedge and downdip of the rupture zone, beneath the coastal area. Furthermore, the observed correlations are consistent with the notion that the forearc is stable above the seismogenic portions of the megathrust, while the updip rate-strengthening portion of the megathrust is maintained in critical state as a result of the stress transfer operated by coseismic and postseismic deformation (Wang and Hu, 2006; Hu and Wang, 2008). The critical state of stress in the coastal area would rather be maintained by interseismic stress build up as aseismic creep proceeds downdip of the coseismic rupture. According to this model, all the deformation is accommodated along the megathrust in the seismogenic zone, no deformation being transferred to the upper plate. This model would explain the correlation between forearc basins or regions with negative gravity anomalies (Wells et al., 2003; Song and Simons, 2003) and seismic asperities. On the other hand, in the creeping areas, the forearc is at or close to critical state, and as a consequence, a small fraction of the convergence has to be accommodated by the upper plate leading to coastal uplift, active faulting in the accretionary prism and thrusting at the transition from the inner to the outer wedge (Fig. 2).

Since critical areas correlate well with aseismic zones, effective basal frictions along aseismic zones can thus be constrained thanks to the critical taper theory. Along the Arauco and Maule accretionary prism, according to the best fit results (Table 1 and Fig. 9c), the effective basal friction ranges between  $\mu_{aseis}^{eff} = 0.25$  to 0.31 with a rather hydrostatic pore pressure ratio in the wedge. If the pore pressure along the megathrust is set equal to the pore pressure in the wedge, then the real static friction would range from  $\mu_{aseis} = 0.4$  to 0.7, in good accordance with friction of clay deduced from laboratory experiments (Logan and Rauenzahn, 1987; Saffer and Marone, 2003; Moore and Lockner, 2004; Ikari et al., 2009). A similar range of effective basal friction values (0.2 to 0.28) has been previously found in other studies of the Nankai, Aleutians and Oregon accretionary prisms (Lallemand et al., 1994).

A stronger effective basal friction with hydrostatic pore pressure is found for the Arauco Peninsula and the Nahuelbuta Range ( $\mu_{aseis}^{e\!f\!f}=0.4$ ), an area suspected to be a recurrent barrier to the propagation of earthquakes. If the internal pore pressure is set equivalent to the megathrust pore pressure, then the static friction along the aseismic megathrust portion downdip of the Maule rupture area would be  $\mu_{aseis} = 0.7$ . This larger value is consistent with the fact that at these depth and temperature conditions (typically 400 °C at 40 km depth, Völker et al., 2011) there is no reason to expect the kind of clay units that may well account for low friction of the upper portions of the megathrust. The rate-strengthening behavior deduced from the postseismic and interseismic models (Lin et al., 2013; Métois et al., 2012; Moreno et al., 2010) associated with the large static friction, low pore pressure and the heterogeneous deformation might explain why the peninsula is acting as a recurrent barrier (Kaneko et al., 2010).

If the frontal aseismic zone is rate-strengthening, then the effective basal frictions found in this study are most probably an average value of the higher friction most probably attained after megathrust rupture as the outer wedge is then brought closer to failure (Wang and Hu, 2006). Along the seismogenic zone, lower effective basal frictions are deduced thanks to the modeling of splay faults with the limit analysis approach ( $\mu_{seis}^{eff} \leq 0.14$ ). Since the Santa Maria backthrust has been activated during the main event, and if we consider the normal sequence of Pichilemu as a consequence of the main shock, the seismogenic friction found is most probably representative of the effective dynamic friction. Different possible explanations can be advanced for the low values determined in this study. An intrinsically low friction is a possibility in principle. This explanation seems improbable as the static friction retrieved for the surrounding aseismic zones is generally larger, and already at the lower end of the range that can be explained with low friction minerals, i.e. the clays of the accretionary prism.

The low effective basal friction in the seismogenic zone could alternatively reflect a high basal pore pressure, either permanent or due to a dynamic increase by thermal-pressurization. Dynamic modeling of earthquake cycles would be suitable to investigate this question.

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### Appendix A. Tapers build up

The topography of individual profiles along the South Chilean forearc was first smoothed as shown in Fig. 3a to avoid high-frequency content. To prevent estimation errors on the mechanical interpretation linked to the smoothing, different smoothing window shapes (triangular and rectangular) and width (10, 25 and 40 km) were tested. For each smoothed profile, the topographic slope and the basal dip were calculated every 100 m. We then compared a profile with its different smoothing to theoretical envelopes (Supplementary Fig. S4). We evaluated the probability that a given portion of a profile follows a critical envelope based on the local linearity of the  $\alpha$ - $\beta$  curve. If the linearity appears obvious for all smoothing, we selected the portion of the profile supposed to be at critical state and reported it on the map in Fig. 5.

Swath profiles were then computed for each segment to obtain a mean and a standard deviation needed for the inversion. The same smoothing technique was applied. The inversion results are based on the profiles obtained with a rectangular 25 km width smoothing window. We also checked the consistency of the inversion results with a triangular window.

#### Appendix B. Effect of megathrust curvature

We ran numerical simulations with the limit analysis approach to validate the applicability of the critical taper theory derived for a triangular wedge, in the case of a curved megathrust. These simulations were run with the Optum-Geo software (2013) which turns out to be more convenient than our own tools due to its user friendly interface (Kristian Kranbbenhoft, personal communication). We consider a 100 km long wedge, and a megathrust with a constant radius of curvature of 100 km, close to the one observed for the megathrust in the Maule rupture area. We assume an internal friction of 30°, a basal friction of 15°, and compute the corresponding critical topographic slope  $\alpha$  for the slab dip  $\beta$  from the relation for a cohesionless triangular wedge (Dahlen, 1984) with a point every 100 m as in our analysis (Supplementary Fig. S5a). We found that the criticality is observed for the same basal friction. In Supplementary Fig. S5b, the topographic slope exceeds by one degree the critical slope, the wedge is thus stable and the whole megathrust is activated. In Supplementary Fig. S5c, the topographic slope is lower by one degree than the critical slope, the wedge is thus unstable, only part of the megathrust is activated and a popup structure develops at the rear wall. The analytical solution is possible for a constant curvature and deserves some attention in the future.

## Appendix C. Robustness of inversion results

Since the weakest parameter of this mechanical analysis is the megathrust dip  $\beta$ , we ran two simple tests in order to evaluate how a change on  $\beta$  could affect the results. In a first test, the megathrust dip  $\beta$  was changed by  $\pm 5^{\circ}$ , and in a second test we applied a coefficient of \*1.5 and \*0.66, that we considered as reasonable errors (Supplementary Fig. S6). These changes only imply a horizontal translation of the taper and do not affect the critical state of the forearc. An error of  $5^{\circ}$  on  $\beta$  implies an error of about  $3^{\circ}$  on the effective basal friction, which is lower than the standard deviation of the probabilities. A coefficient error induces a change of dip of the critical envelope leading to a different couple of internal friction–internal pore fluid pressure. If the coefficient is lower than 1.5, the resulting error is again smaller than the standard deviation of the probability distribution.

#### Appendix D. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2013.07.037.

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