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Constraining the strength of megathrusts from fault geometries and application to the Alpine collision zone

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ABSTRACT

Using Coulomb wedge solutions, we show that the effective strength of megathrusts (μ_b') can be determined from the geometry of out-of-sequence thrusts cutting through an accretionary or orogenic wedge. The method is first tested on central Chilean margin for which it yields a frictional strength of $\mu_b' = 0.053$ ($+0.043/-0.024$). The inferred value agrees well with previous strength estimates and with the tectonic response of the central Chilean wedge to 2010 M_w 8.8 Maule earthquake. We then use the approach to constrain the strength of the collision megathrust of the central European Alps ∼30–20 million years ago. We find that the collision megathrust had a strength of $\mu_b' = 0.065$ ($+0.035/-0.026$), which is similarly low than the strength of subduction megathrusts. The result is integrated into a static force balance model to examine potential implications of a weak megathrust for the Alpine orogeny. The model results suggest that the Alpine megathrust supported a mean maximum elevation of ∼2,000 m and that growth of the wedge up to this elevation supported a switch from contractional to extensional tectonics in the interior of the Alps around 20 Ma. Finally, using the example of the Himalayas, we show how the strength of megathrusts may be also derived from the geometry of crustal ramps, which provides a valuable alternative if details on out-of-sequence thrusts are missing.

1. Introduction

Megathrusts are large-scale thrust faults that form along the interface of convergent plate margins and cut from the Earth's surface down into the mantle lithosphere. Their physical properties are a major research topic not only because of the large seismic hazard these faults bear (e.g. Plafker, 1965; Molnar and England, 1990; Lamb, 2006; Gao and Wang, 2014). Megathrusts play also a fundamental role in the tectonics of convergent plate margins. In particular, their effective strength is a critical parameter for mountain building, as it has a great impact e.g. on the stress field within an orogen, on the magnitude of resistive forces counteracting plate convergence, or on accretionary processes and related mass flux (e.g. van den Beukel, 1992; Wang and He, 1999; Lamb, 2006; Seno, 2008; Meade and Conrad, 2008; Seno, 2009; Angiboust et al., 2015). Having good constraints on the mechanical properties of a megathrust is therefore essential for scrutinizing the tectonic evolution of an orogen. However, while there is rapidly growing information on megathrusts at subduction zones (hereinafter subduction megathrusts), very little is known about their counterpart at collision zones (hereinafter collision megathrusts). Indeed, the term megathrust itself is traditionally associated with a subduction zone setting, but the existence of a basal fault or detachment beneath collisional orogens is generally not questioned. On the contrary, the subduction of continental crust to great depths and its partial recycling into the mantle (e.g. Chopin, 1984; Froitzheim et al., 2016; Ingalls et al., 2016) require a continuous, deep-reaching plate boundary fault similar to the one at subduction zones.

Thermomechanical models based on surface heat flow observations, earthquake distribution, or force balancing of topographic loading indicate that subduction megathrusts worldwide are mechanically very weak (e.g. Wang and He, 1999; Lamb, 2006; Seno, 2009; Gao and Wang, 2014). The inferred strengths translate to effective friction coefficients of $\mu_b' < 0.1$, i.e. about one order of magnitude smaller than estimates derived from continental borehole data or laboratory experiments (e.g. Byerlee, 1978; Brudy et al., 1997). Moreover, a similar mechanical weakness has been deduced from focal mechanisms for the surroundings of subduction megathrusts, suggesting that forearcs are in general low-stress environments (Hardebeck, 2015). Interestingly, comparable stress and strength conditions are also inferred for the San Andreas continental transform fault, despite the different tectonic setting (Hardebeck and Michael, 2004; Hardebeck, 2015). This leads to the question, if collision zones and their megathrust are sim-

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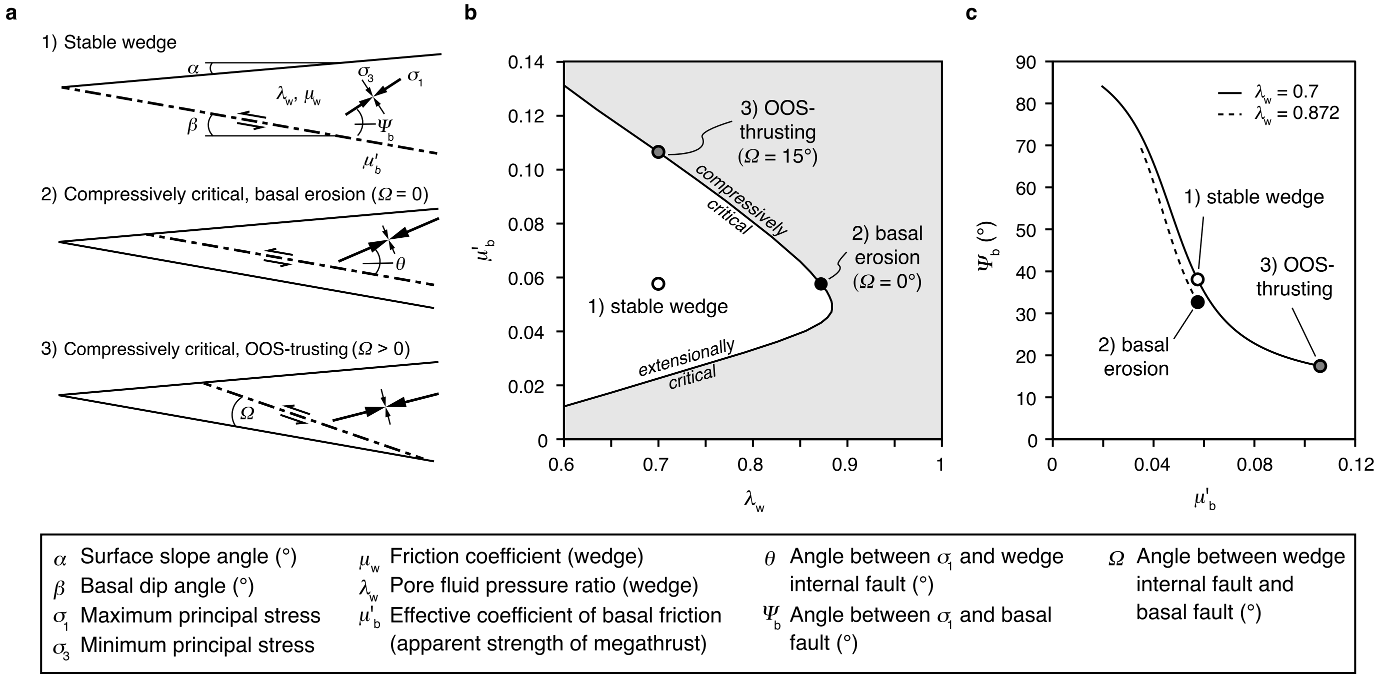

Fig. 1. Coulomb wedge model setup and concept. a) Schematic illustration of three different mechanical states of a Coulomb wedge. Configuration 1 shows a stable wedge that deforms only elastically. The potential failure plane or plastic slip line (dot-dashed line) is the basal fault. Configurations 2 and 3 show compressively critical wedges that react by thrust faulting. In 2, the wedge and the basal fault have the same strength. The plastic slip line lies within the wedge and is parallel oriented to the basal fault ($\Omega = 0$). This is the ideal state of basal erosion. In 3, the wedge is slightly stronger than the basal fault and the plastic slip line makes an angle $\Omega > 0°$ to the basal fault. The setting resembles out-of-sequence (OOS) thrusting. b) Configurations in (a) depicted in the $\lambda_w - \mu'_b$ space. c) Elastic stress paths showing angle Ψ_b as function of λ_w and μ'_b. Configurations in (a) are indicated by open and closed circles.

ilarly weak. The difficulty in answering this question is that active megathrusts are not directly accessible and that the methods used to determine their effective strength at subduction zones are problematic to apply to collisional orogens, especially to fossil ones.

An alternative to determine the effective strength of megathrusts is given by the Coulomb wedge model, which describes the first order mechanics of orogenic wedges within the frictional (or ideal plastic) regime (e.g. Dahlen, 1984; Wang and Hu, 2006; Suppe, 2007). However, its conventional application depends on critical presumptions about the pore fluid pressure ratio in the wedge λ_w (i.e. the ratio of fluid pressure to lithostatic pressure) and wrong estimates may yield highly erroneous results (e.g. Suppe, 2007). To overcome this problem, we follow another Coulomb wedge approach, in which λ_w is self-constrained by taking the geometry of out-of-sequence thrusts (OOSTs) into account (cf. Davis and Huene von, 1987). We test the method using the example of the central Chilean subduction zone, for which independent strength constraints are available. Afterwards, we apply the Coulomb wedge model to the central European Alps to determine the effective strength of the collision zone during the main mountain building phase, i.e. ~30 to 20 Ma. The results are implemented in a static force balance analysis to discuss a potential relationship between the topographic growth of the Alps and the larger-scale tectonic evolution of the orogen. We close the present work with a brief discussion of the potential application of the Coulomb wedge approach to crustal ramps.

2. Methods

2.1. Coulomb wedge model

To constrain the effective strength of megathrusts and orogenic wedges from the geometry of thrust faults, we use the Coulomb wedge model (e.g. Dahlen, 1984; Davis and Huene von, 1987; Wang and Hu, 2006; Suppe, 2007). The model calculates the orientation of the maximum principal stress σ_1 and predicts the stress conditions under which a wedge is in a mechanically stable or unstable state. A uniform, noncohesive Coulomb wedge is defined by its geometry, given by the surface slope α and the basal dip angle β, and by the friction coefficient of the wedge material μ_w (Fig. 1a). The mechanical state of a wedge depends on two factors: (*i*) the pore fluid pressure ratio in the wedge λ_w, which controls the effective strength of the wedge material $\mu'_w = \mu_w(1-\lambda_w)$, and (*ii*) the effective coefficient of basal friction μ'_b, (also apparent or effective strength of a megathrust). The parameters μ'_b and λ_w are not fixed but variable and different pairs of values result in distinct mechanical conditions. This dependency is visualized in the $\lambda_w - \mu'_b$ space (Fig. 1b). For the purpose of the present work, it suffices to consider the major principal states in which a Coulomb wedge can be.

A wedge is in a stable state, if it overlies a weaker basal fault of intermediate strength (configuration 1 in Fig. 1). The basal fault represents the potential failure plane (plastic slip line) and the wedge deforms only elastically (Dahlen, 1984; Wang and Hu, 2006). If μ'_b is sufficiently low, the wedge is in an extensionally critical state and reacts by normal faulting. Conversely, if μ'_b is sufficiently high, the wedge is in a compressively critical state and reacts by thrust faulting. The plastic slip lines lie within the wedge and form at angle θ to σ_1, where $\theta = 45° - 0.5\tan(\mu_w)^{-1}$. Likewise, the plastic slip lines make an angle Ω to the basal fault, which is given by $\Omega = \theta - \Psi_b$, where Ψ_b is the angle between the basal fault and the orientation of σ_1 (note that a conjugate set of plastic slip lines could also form at an angle $\theta + \Psi_b$ but is not considered herein for simplicity). The magnitude of Ω depends on the ratio between μ'_w and μ'_b. If $\mu'_w/\mu'_b = 1$, the wedge is mechanically indistinguishable from the basal fault and the plastic slip lines are oriented parallel to the fault, i.e. $\Omega = 0$ (configuration 2 in Fig. 1). If $\mu'_w/\mu'_b > 1$, the wedge and the basal fault are mechanically distinct and Ω is greater than zero and increases together