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Application of the critical Coulomb wedge theory to hyper-extended, magma-poor rifted margins

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ABSTRACT

The Critical Coulomb Wedge Theory (CCWT) has been extensively used in compressional tectonics to resolve the shape of orogenic or accretionary prisms, while it is less applied to extensional and gravitational wedges despite the fact that it can be described by the same equation. In particular, the hyper-extended domain at magma-poor rifted margins, forming the oceanward termination of extended continental crust, satisfies the three main requirements of the CCWT: 1) it presents a wedge shape, 2) the rocks forming the wedge are completely brittle (frictional), and 3) the base of the wedge corresponds to a low friction décollement. However hyper-extended margins present a fully frictional behaviour only for a very thin crust; therefore this study is limited to the termination of hyper-extended continental crust which deforms in the latest stage of continental rifting. In this paper we define a method to measure the surface slope and the basal deep of this wedge that we apply to 17 hyper-extended, magma-poor rifted margins in order to compare the results to the values predicted by the CCWT. Because conjugate pairs of hyper-extended, magma-poor rifted margins are commonly asymmetric, due to detachment faulting, the wedges in the upper and lower plate margins corresponding respectively to the hanging wall and footwall of the detachment system are different. While the stress field in the upper plate wedge corresponds to a tectonic extensional wedge, the one in the lower plate matches that of a gravity extensional wedge. Using typical frictional properties of phyllosilicates (e.g. clays and serpentine), the shape of the hyper-extended wedges can be resolved by the CCWT using consistent fluid overpressures. Our results show that all lower plate margins are gravitationally stable and therefore have a close to critical shape whereas the tectonic extensional wedges at upper plate margins are critical, sub or sup critical due to the detachment initial angle and the duration of the tectonic activity. In this paper we discuss the geometry and structural evolution of the most distal parts of hyper-extended continental margins and the formation of extensional allochthons during hyper-extension using the CCWT theory.

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1. Introduction

High resolution long-offset seismic reflection images are able to resolve the wedge shape termination of the hyper-extended continental crust at magma-poor rifted margins. Deformation in hyper-extended margins has been investigated and discussed using numerical modelling (Brune et al., 2014; Huismans and Beaumont, 2011), seismic interpretations (Reston and McDermott, 2011; Sutra and Manatschal, 2012), kinematic reconstructions and field observations (Manatschal, 2004). Although the mode of deformation, structural evolution, physical properties and rheology of hyper-extended crust is controversial, it is commonly accepted that the final deformation of this domain is intimately linked to fluids and hydration reactions that occur in the brittle/frictional field (Pérez-Gussinyé and Reston, 2001). Indeed, these reactions lead to serpentinisation of the uppermost mantle and to the alteration of the continental crust, which are associated to a decrease of rocks frictional properties. Observations on field analogues in the Alps (Florineth and Froitzheim, 1994; Manatschal et al., 2006) and seismic interpretations (Reston et al., 1996) demonstrate that the contact between the continental basement and the underlying serpentinised mantle is a décollement surface. After more than thirty years of intense research at hyper-extended magma-poor rifted margins, it appears that the termination of hyper-extended margins can be described as a brittle (frictional), wedge-shaped body,

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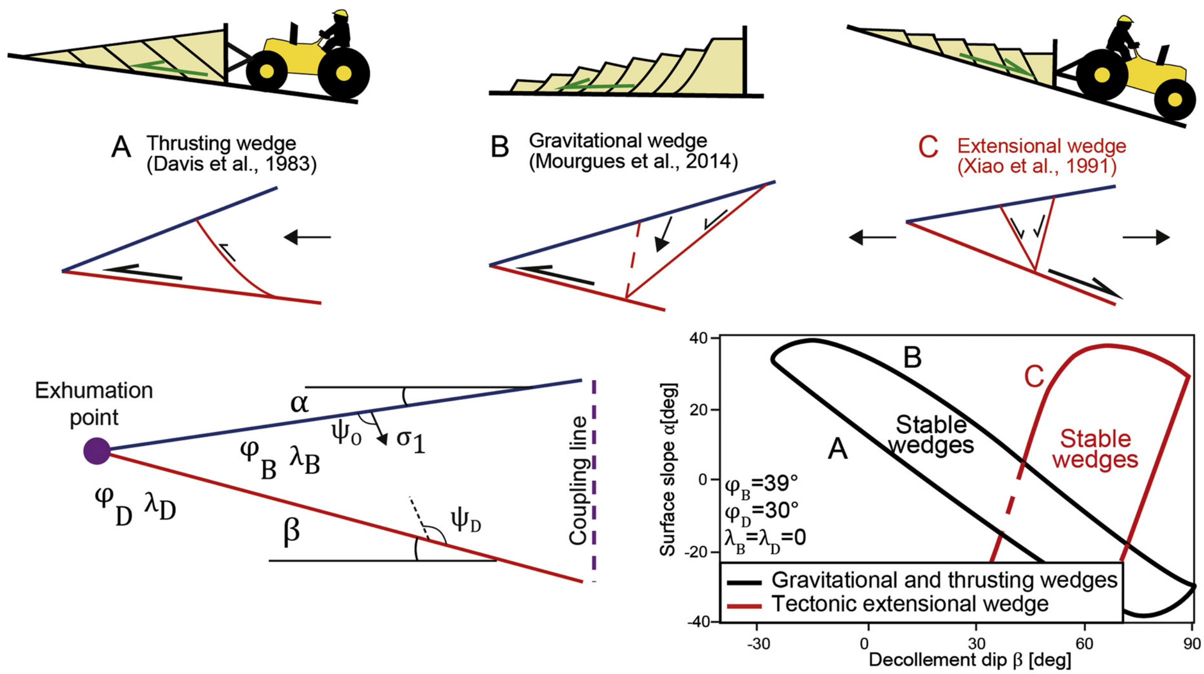

Fig. 1. Visual representation of the three different types of wedges. Schematic cross section of a wedge with geometrical attributes and physical parameters used in the CCWT (see Section 2). Stability envelopes for critical Coulomb wedge (dry case) in compression and extension.

whose base is a décollement corresponding to the crust–mantle boundary (Pérez-Gussinyé and Reston, 2001). Accordingly, hyper-extended margins fulfil the fundamental requirements of the Critical Coulomb Wedge Theory (CCWT), which describes the stability limits of a frictional wedge on a décollement.

The CCWT has been applied to many compressive systems such as thrust and fold belts or accretionary prisms (Davis et al., 1983), as well as in active extensional setting (Xiao et al., 1991). The tapering geometry of thinned continental crust at rifted continental margins has previously been recognised and quantitatively described by Davis and Kusznir (2002) and Osmundsen and Redfield (2011). However CCWT has not been applied to hyper-extended rifted margins. Testing the CCWT on the hyper-extended part of magma-poor rifted margins is new and may help to understand deformation processes involved in hyper-extended magma-poor rifted margins. Therefore we aim to set up a methodology to recognise and measure the basal dip and the surface slope of the wedge in hyper-extended margins, referred to as the Hyper-Extended Continental Wedge (HECW). The HECW measurements are then plotted and compared with the CCWT using physical properties of rocks from hyper-extended domains to highlight the control by CCWT on the final shape of the continental crust termination.

2. The Critical Coulomb Wedge Theory (CCWT)

A series of papers were published in the 1980s about the mechanics of fold-and-thrust belts and accretionary wedges, comparing those geological features with a pile of sand in front of a moving bulldozer (Dahlen, 1984; Davis et al., 1983). The main results of these studies on cohesionless materials are that active accretionary wedges deform until reaching a critical shape, which corresponds to an internal state of stress on the verge of Coulomb failure everywhere (Dahlen, 1984). Once this critical stress state has been reached, sliding occurs along the décollement without any deformation within the wedge (Fig. 1). The critical angles of the taper depend on the internal angle of friction of the material, the friction along the décollement and the pore fluid pressure. The thrusting wedge was defined with a basal shear sense oriented toward the thinner part of the wedge (Fig. 1A).

If a frictional wedge becomes unstable due to a change of physical parameter, without any tectonic compressive or extensional forces involved, it can collapse seawards (towards the thinnest part of the wedge), until it returns to a stable state. The stable state for this gravitational wedge corresponds to the upper limit (Fig. 1B) of the CCWT envelope in Dahlen (1984) (see also Mourgues et al., 2014 for a more developed version). The shear stress at the base is oriented towards the thinnest part of the wedge (Fig. 1B). This setting is characteristic of gravitational spreading in orogenic wedges and gravitational gliding along passive margins, as exemplified by submarine landslides. Xiao et al. (1991) extended the CCWT to the context of active extensional wedges, where the taper angle decreases with the retreat of the wall until it reaches the critical taper-shape (Fig. 1C). In this "extensional wedge", the basal shear stress is oriented toward the inner part of the wedge (Fig. 1C).

The stability envelopes of tectonic extensional, compressional and gravitational critical wedges are given by the same equation as those described by Dahlen (1984) and later corrected for large taper angle by Wang et al. (2006), Mourgues et al. (2014) and by Yuan et al. (2015). ψ_D is the angle between σ_1 and the décollement and ψ_0 the angle between σ_1 and the surface slope, dipping at α. Therefore, the stability of a frictional wedge depends on the décollement and internal friction coefficients (φ_B, φ_D) and on the fluid pressure (λ_B, λ_D) in the décollement and within the wedge, as shown by Yuan et al. (2015). Indeed:

$$\alpha + \beta = \psi_D - \psi_0 \tag{1}$$

$$\psi_D = \frac{1}{2}\arcsin\left[\left(\frac{1-\lambda_D}{1-\lambda_B}\right)\frac{\sin(\varphi_D)}{\sin(\varphi_B)} + \left(\frac{\lambda_D-\lambda_B}{1-\lambda_B}\right)\sin(\varphi_D)\cos(2\psi_0)\right] - \frac{1}{2}\varphi_D \tag{2}$$

$$\psi_0 = \frac{1}{2}\arcsin\left(\frac{\sin(\alpha')}{\sin(\varphi_B)}\right) - \frac{1}{2}\alpha' \tag{3}$$

$$\alpha' = \arctan\left[\left(\frac{1-\frac{\rho_f}{\rho}}{1-\lambda_B}\right)\tan\alpha\right] \tag{4}$$

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