Earth and Planetary Science Letters 488 (2018) 27–35

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

"Virtual shear box" experiments of stress and slip cycling within a subduction interface mélange

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ARTICLE INFO

Article history:
Received 21 August 2017
Received in revised form 18 December 2017
Accepted 29 January 2018
Available online xxxx
Editor: R. Bendick

Keywords:
subduction
mélange
stress
numerical modeling
Chrystalls Beach Complex
strain transients

ABSTRACT

What role does the progressive geometric evolution of subduction-related mélange shear zones play in the development of strain transients? We use a "virtual shear box" experiment, based on outcrop-scale observations from an ancient exhumed subduction interface – the Chrystalls Beach Complex (CBC), New Zealand – to constrain numerical models of slip processes within a meters-thick shear zone. The CBC is dominated by large, competent clasts surrounded by interconnected weak matrix. Under constant slip velocity boundary conditions, models of the CBC produce stress cycling behavior, accompanied by mixed brittle-viscous deformation. This occurs as a consequence of the reorganization of competent clasts, and the progressive development and breakdown of stress bridges as clasts mutually obstruct one another. Under constant shear stress boundary conditions, the models show periods of relative inactivity punctuated by aseismic episodic slip at rapid rates (meters per year). Such a process may contribute to the development of strain transients such as slow slip.

1. Introduction

Subduction megathrust faults can exhibit a wide range of slip behaviors (e.g., Ide et al., 2007; Peng and Gomberg, 2010). Some are interseismically locked to ∼20–30 km depths, accumulating stress slowly between large earthquakes, and transitioning to steady aseismic creep at greater depths where temperatures exceed those required for quartz plasticity (>350 °C; e.g., Hyndman and Wang, 1993). Other megathrust faults can experience punctuated slow slip events (SSEs) – characterized by aseismic creep that occurs at rates that are subseismic but faster than plate boundary averages – that last for days to years (e.g., Miyazaki et al., 2006; Peng and Gomberg, 2010). Slow slip rates are commonly 0.15–1.0 $\mathrm{m\,yr^{-1}}$, and up to ∼2 $\mathrm{cm\,day^{-1}}$ (e.g., Miyazaki et al., 2006; Schwartz and Rokosky, 2007; Wallace and Beavan, 2010; Bartlow et al., 2014). Transient slow slip is commonly associated with episodic tectonic tremor and/or microseismicity, and may play a significant role in stress cycling at subduction zones (Ide et al., 2007; Schwartz and Rokosky, 2007; Peng and Gomberg, 2010). Many SSEs occur at depths of >20–30 km, although they have also been detected at <5–20 km depths (e.g., Wallace et al., 2012; Araki et al., 2017). Several recent explanations for shallow episodic tremor and slip (ETS) focus on the transitional frictional behavior of clays, and the effects of evolving clay mineralogy on frictional stability and strength with increasing pressure and temperature, based on experimental deformation of clay- and quartz-rich gouges (e.g., Ikari and Saffer, 2011; den Hartog et al., 2012; Ikari et al., 2013, 2015). Other explanations relate to frictional stability variations resulting from low normal stresses associated with zones of highly overpressured fluids, and the effects of heterogeneous stresses and materials (e.g., Scholz, 1998, 2002; Liu and Rice, 2005, 2007; Skarbek et al., 2012; Wang and Bilek, 2014; Saffer and Wallace, 2015, and references therein).

Laboratory experiments on clay- and quartz-rich gouges have documented the effects of evolving clay mineralogy on frictional stability and strength with pressure and temperature (e.g., Ikari et al., 2013; Saito et al., 2013). Such shear box experiments typically deform mm-thick gouge layers. In contrast, studies of exhumed subduction faults suggest that at $\gtrsim$1 km depths, the subduction interface between upper and lower plates at convergent margins can be hundreds of meters wide, with multiple discrete, anastomosing, simultaneously active fault strands organized within 5–35 m thick tabular high-strain zones (Rowe et al., 2013). Exhumed subduction thrusts also exhibit a complex rheological mix of materials that have experienced mixed brittle fracturing, ductile shear, and solution-precipitation creep, accompanied by transient

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https://doi.org/10.1016/j.epsl.2018.01.035
0012-821X/

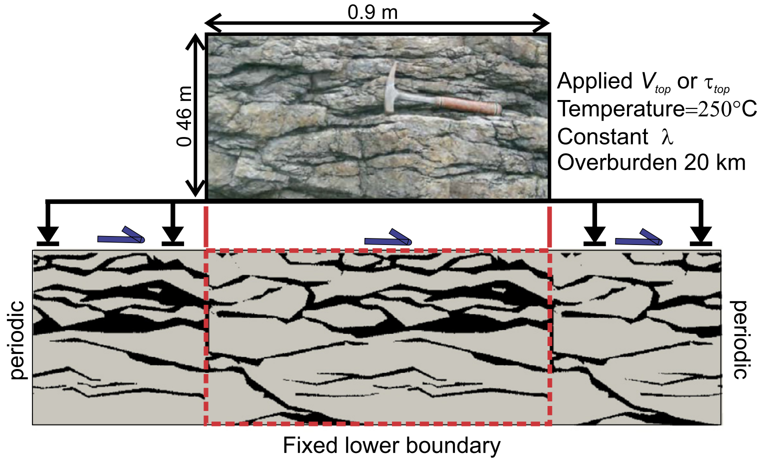

Fig. 1. Model initial set up and boundary conditions. Model set up (bottom) is based on a clast-dominated outcrop from the Chrystalls Beach Complex from Fagereng and Sibson (2010) (top). Model dimensions are repeated 45 cm to either side to avoid boundary effects, and we impose a thin 1 cm-thick clast layer at the top. Periodic material flow and free velocity boundary conditions were applied at the left and right boundaries. Material leaving the right-hand boundary is reinjected at the left-hand boundary. Black represents mudstone matrix and grey regions are competent sandstone clasts. Two types of experiments were run: in experiment 1 we applied a constant shear slip velocity at the upper boundary (V_{top}); in experiment 2 we applied a constant shear stress at the upper boundary (τ_{top}; see text for details). See Supplement S1 for more details regarding the numerical model and rheology.

near-lithostatic fluid pressure cycling (e.g., Bachmann et al., 2009; Fagereng and Sibson, 2010; Fagereng, 2011a; Hayman and Lavier, 2014). To date, only a few attempts have been made to capture such complex rheological interactions using laboratory and numerical experiments (e.g., Skarbek et al., 2012; Reber et al., 2015).

Here, we attempt to understand subduction zone slip behavior at scales greater than those attained in laboratory experiments, by simulating a "virtual shear box" using numerical modeling. We deform a two-phase mélange, volumetrically dominated by large competent clasts, surrounded by a weak interconnected matrix. Our results suggest that geometric reorganization within a subduction mélange can drive significant oscillations in shear stress and/or slip velocities of durations and frequencies of months to years.

2. Chrystalls Beach Complex: an ancient subduction analogue

The initial clast distribution and rock materials in our model domain are based on field exposures of the Chrystalls Beach Complex (CBC), New Zealand. The CBC is a <4 km thick tectonic mélange deformed along an ancient subduction interface between 175–155 Ma, at <550 MPa and ∼300 °C peak metamorphic conditions (Fagereng and Cooper, 2010; Fagereng, 2011a, and references therein). Within the CBC, asymmetric competent clasts of sandstone, chert and basalt – themselves derived from non-coaxial shear and layer-perpendicular shortening of original bedding – are surrounded by a weak phyllitic matrix (Fagereng, 2011a). The frequency-size distributions of competent lenses follow a power-law distribution, where the power law exponent depends on the volume ratio of competent to incompetent material (Fagereng, 2011b). The competent clasts contain internal fault-fracture networks comprising extension fractures that are dominantly oriented perpendicular to clast long axes (Fagereng, 2011b).

The CBC has been intensely sheared in a mixed continuous-discontinuous style, where discontinuous deformation records localized seismic and/or aseismic slip adjacent to volumetrically continuous fabrics that have experienced aseismic flow (Fagereng and Sibson, 2010, and references therein). Exposures express a complex superposition of deformation structures, indicating formation in a time-progressive sequence of increasing cohesive strength (Fagereng, 2011a). Fagereng (2011a) has suggested that within the CBC, different mineral-scale deformation mechanisms, the degree of continuous versus discontinuous deformation, and bulk rheological behavior, all depend on the local volumetric ratio of competent clasts to matrix, and that transient, locally high fluid pressures were required to form slickenfibres, extension fractures, and vein deposits.

3. The "virtual shear box"

The finite element code SULEC (Buiter and Ellis, 2012) is used to model aseismic slip in a "virtual shear box" that represents a portion of an actively deforming subduction thrust interface, which may itself be up to hundreds of meters thick (Rowe et al., 2013). We use a representative clast-dominated mélange configuration from the CBC (Fagereng and Sibson, 2010), characterized by ∼70% competent clasts and ∼30% mudstone matrix (Fig. 1). The exposure is representative of a clast-dominated zone within the mélange; this differs from zones where the matrix is volumetrically dominant, and bulk steady creep is inferred to have occurred (Fagereng and Sibson, 2010). We assume that the current observed outcrop configuration approximates the subduction system immediately prior to exhumation, such that it is appropriate for modeling deformation at peak metamorphic conditions. Therefore, we do not model a time-progressive increase in clast cohesion – rather we hold the model domain at a constant depth for the duration of the model run (which lasts for months–decades).

We apply a composite matrix rheology, including a combination of pressure-sensitive Coulomb yield and linear precipitation-solution creep, derived from a microphysical model of phyllosilicate gouge (Niemeijer and Spiers, 2005; den Hartog and Spiers, 2013; Fagereng and den Hartog, 2017), and viscous non-linear dislocation creep (Supplement S1), (Mares and Kronenberg, 1993; Bukovská et al., 2016). At each time-step, the deformation mechanism (frictional shear combined with pressure solution, or non-linear creep) is determined at each node as the mode of lowest yield stress. The strong cohesive clasts may only deform brittlely, and have a Byerlee friction coefficient of 0.72, and cohesive strength of 70 MPa (see Supplement S1). Our experiments are run at 250 °C, lithostatic pressure corresponding to 20 km depth (520 MPa, assuming a bulk rock density of 2650 kg m^{-3}), and constant fluid pressure ratios $\lambda = (P_f/\sigma_z)$ of 0.67, 0.8 or 0.9, where P_f is fluid pressure, and σ_z is overburden stress. Here we assume that fluid pressure is greater than hydrostatic (i.e., $\lambda > 0.38$), and