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A viscoplastic shear-zone model for deep (15–50 km) slow-slip events at plate convergent margins

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ABSTRACT

A key issue in understanding the physics of deep (15–50 km) slow-slip events (D-SSE) at plate convergent margins is how their initially unstable motion becomes stabilized. Here we address this issue by quantifying a rate-strengthening mechanism using a viscoplastic shear-zone model inspired by recent advances in field observations and laboratory experiments. The well-established segmentation of slip modes in the downdip direction of a subduction shear zone allows discretization of an interseismic forearc system into the (1) frontal segment bounded by an interseismically locked megathrust, (2) middle segment bounded by episodically locked and unlocked viscoplastic shear zone, and (3) interior segment that slips freely. The three segments are assumed to be linked laterally by two springs that tighten with time, and the increasing elastic stress due to spring tightening eventually leads to plastic failure and initial viscous shear. This simplification leads to seven key model parameters that dictate a wide range of mechanical behaviors of an idealized convergent margin. Specifically, the viscoplastic rheology requires the initially unstable sliding to be terminated nearly instantaneously at a *characteristic velocity*, which is followed by stable sliding (i.e., slow-slip). The characteristic velocity, which is on the order of $<10^{-7}$ m/s for the convergent margins examined in this study, depends on the (1) effective coefficient of friction, (2) thickness, (3) depth, and (4) viscosity of the viscoplastic shear zone. As viscosity decreases exponentially with temperature, our model predicts faster slow-slip rates, shorter slow-slip durations, more frequent slow-slip occurrences, and larger slow-slip magnitudes at warmer convergent margins.

1. Introduction

Deep (15–50 km) slow-slip events (D-SSEs) occur along the upper interface of a subducting slab (Shelly et al., 2006; Ide et al., 2007a) at the brittle–ductile transition (BDT) depths (Peacock et al., 2011) between the up-dip seismogenic megathrust and the down-dip aseismic creeping zone (Schwartz and Rokosky, 2007; cf., Gao and Wang, 2017) (Figs. 1a and 1b). Individual events accommodate a few cm motion, rupture up to >1000 s km^2, last a few days to a few years (e.g., Dragert et al., 2001; Szeliga et al., 2008), are accompanied by tectonic tremors and/or microseismicity (Dragert et al., 2001; Obara and Kato, 2016; Gao and Wang, 2017), and have maximum stress drops of 10–100 kPa (Ide et al., 2007b; Brodsky and Mori, 2007). When the continental interior above a subducting slab is fixed, slow-slip motion in a forearc region may be expressed in two contrasting modes: (1) alternating fast and slow episodes of landward motion with the slow-slip phase moving at a rate slower than the speed of the subducting slab (i.e., $V_{HW} < V_{FW}$ and V_{HW} and $V_{FW} > 0$) (Fig. 1c), or (2) alternating landward and trenchward motion with the hanging wall moving in the opposite direction of the subducting footwall motion (i.e., $V_{HW} < 0$ and $V_{FW} > 0$) (Fig. 1d). As shown in Figs. 1c and 1d, V_{HW} is the hanging-wall/overriding-plate velocity, and V_{FW} is the footwall/subducting-plate velocity; they are positive in the landward direction. Note that the slow-slip mode via alternating fast and slow landward motion has not been documented formally, although the geodetic observations do hint their existence despite the large noise-signal ratios (e.g., Dragert et al., 2001).

Most D-SSEs are quasi-periodic (e.g., Szeliga et al., 2008), interpreted as a result of conditionally stable sliding governed by rate-state friction such as the work of Liu and Rice (2007) and Liu (2013) based on a gabbro rate-state friction law (He et al., 2007). As subduction shear zones are composed of felsic and mafic rocks with drastically different rheological properties (e.g., Grove et al., 2008; Hayman and Lavier, 2014), the composite effects of mixed rock rheology must be considered. In this regard, He et al. (2013) demonstrated experimentally that the presence of a trace amount of quartz in gabbro gouge under the deep slow-slip condi-

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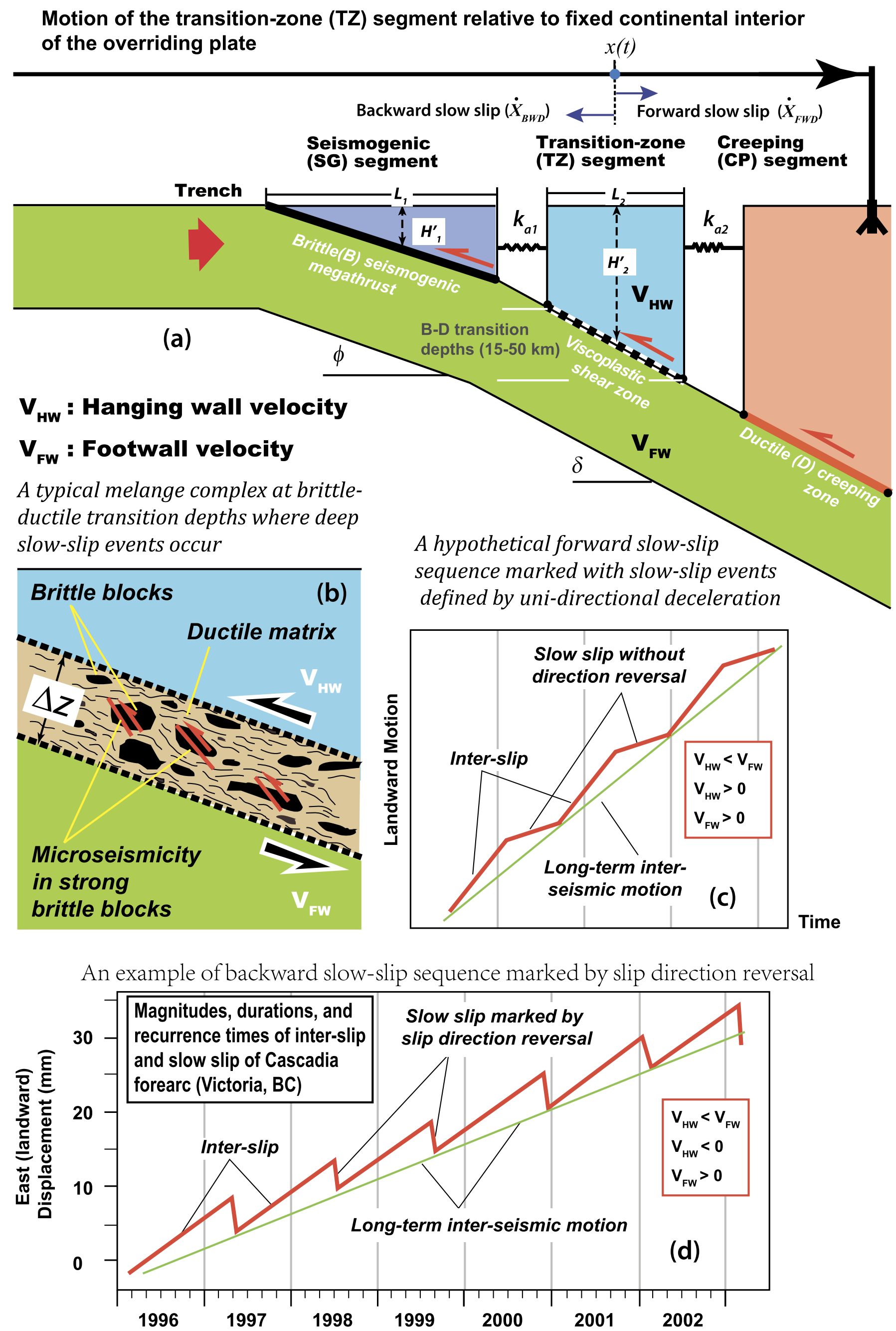

Fig. 1. (a) Forearc division of an overriding plate at a convergent margin: SG, seismogenic segment bounded below by a brittle seismogenic fault; TZ, brittle–ductile transition-zone segment bounded below by a viscoplastic shear zone along which deep slow-slip events occur; CP, creeping segment bounded by an aseismic ductile shear zone. (b) A conceptualized deep slow-slip shear zone that consists of strong and partially interlocked brittle blocks (mafic rocks and/or strong mineral phases cut by brittle faults and fractures) surrounded by ductile matrix (felsic and phyllosilicate rocks with mylonitic fabrics). (c) A hypothetical mode of a slow-slip sequence expressed by alternating fast and slow landward motion. (d) A slow-slip sequence characterized by alternating landward and trenchward motion as recorded in the Cascadia forearc, simplified after Rogers and Dragert (2003).

tions would lead to stable frictional sliding, which puts the results of Liu and Rice (2007) and Liu (2013) in question.

Assuming the onset of a slow-slip event is unstable due to rate-weakening governed by rate-state friction, dilatancy (e.g., Segall et al., 2010) and high-velocity strengthening (e.g., Shimanmoto and Noda, 2014) were proposed as possible stabilization mechanisms during slow-slip events. For dilatancy to work, particles in the shear zone must be rigid, in frictional contact, and closely compacted (Reynolds, 1885). However, the clast-supported texture required by the dilatancy mechanism contrasts the characteristic *ductile* matrix-supported texture of exhumed subduction shear zones from the D-SSE depths (e.g., Grove et al., 2008; Hayman and Lavier, 2014; Angiboust et al., 2015) (Fig. 1b). The high-velocity strengthening mechanism is also problematic, as it has never been confirmed experimentally with the lithology and pressure–temperature conditions relevant to D-SSEs (e.g., He et al., 2013).

Temperature as a state variable, neglected in the existing modeling efforts (e.g., Liu and Rice, 2007), plays a dominant role in frictional sliding under the brittle–ductile transition temperatures (400–600 °C) (Chester, 1994). Additionally, shear-zone thickness, which is also not treated in the existing slow-slip models (e.g.,