Frictional and Lithological Controls on Shallow Slow Slip at the Northern Hikurangi Margin

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November 21, 2022

Abstract

Slow slip events (SSEs) have been identified at subduction zones globally as an important link in the continuum between elastodynamic ruptures and stable creep. The northern Hikurangi margin is home to shallow SSEs which propagate to within 2 km of the seafloor and possibly to the trench, providing insights into the physical conditions conducive to SSE behavior. We report on a suite of friction experiments performed on protolith material entering the SSE source region at the Hikurangi margin, collected during the International Ocean Discovery Program Expedition 375. We performed velocity stepping and slide-hold-slide experiments over a range of fault slip rates, from plate rate (5 cm/yr) to ~1 mm/s and quantified the frictional velocity dependence and healing rates for a range of lithologies at different stresses. The friction velocity dependence *(a-b)* and critical slip distance D_c increase with fault slip rate in our experiments. We observe a transition from velocity weakening to strengthening at slip rates of ~0.3 µm/s. This velocity dependence of D_c could be due to a combination of dilatant strengthening and a widening of the active shear zone at higher slip rates. We document low healing rates in the clay-rich volcaniclastic conglomerates, which lie above the incoming plate basement at least locally, and relatively higher healing rates in the chalk lithology. Finally, our experimental constraints on healing rates in different input lithologies extrapolated to timescales of 1-10 years are consistent with the geodetically-inferred low stress drops and healing rates characteristic of the Hikurangi SSEs.

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Abstract:

Slow slip events (SSEs) have been identified at subduction zones globally as an important link in the continuum between elastodynamic ruptures and stable creep. The northern Hikurangi margin is home to shallow SSEs which propagate to within 2 km of the seafloor and possibly to the trench, providing insights into the physical conditions conducive to SSE behavior. We report on a suite of friction experiments performed on protolith material entering the SSE source region at the Hikurangi margin, collected during the International Ocean Discovery Program Expedition 375. We performed velocity stepping and slide-hold-slide experiments over a range of fault slip rates, from plate rate (5 cm/yr) to ~1 mm/s and quantified the frictional velocity dependence and healing rates for a range of lithologies at different stresses. The friction velocity dependence (a-b) and critical slip distance Dc increase with fault slip rate in our experiments. We observe a transition from velocity weakening to strengthening at slip rates of ~0.3 μm/s. This velocity dependence of Dc could be due to a combination of dilatant strengthening and a widening of the active shear zone at higher slip rates. We document low healing rates in the clay-rich volcaniclastic conglomerates, which lie above the incoming plate basement at least locally, and relatively higher healing rates in the chalk lithology. Finally, our experimental constraints on healing rates in different input lithologies extrapolated to timescales of 1-10 years are consistent with the geodetically-inferred low stress drops and healing rates characteristic of the Hikurangi SSEs.

Keywords:

Slow earthquakes, Hikurangi, Friction, Slow slip

Key points:

- We quantify frictional stability and healing behavior of input material to the subduction plate interface at the northern Hikurangi margin
- Increasing frictional stability and critical slip distance with velocity may be key mechanisms responsible for shallow slow slip
- Velocity dependence of critical slip distance may be from a combination of dilatant strengthening and distributed slip at higher slip rates

1. Introduction:

Slow slip events (SSEs), lasting for days to months, have been widely recognized as an important part of the continuum bridging fast, elastodynamic ruptures and stable fault creep at plate boundaries globally (*Ide et al., 2007; Peng and Gomberg, 2010; Bürgmann, 2018*). These types of slip modes are particularly important because of the role they play in the seismic cycle and the accommodation of plate motion, and because of the clues they provide about plate interface rheology. In some cases, SSEs are thought to trigger ordinary fast earthquakes by loading adjacent fault patches (*Kato et al., 2012; Meng et al., 2015*). In other cases, SSEs have been triggered (*Araki et al., 2017; Wallace et al., 2017*) or arrested (*Wallace et al., 2014*) by nearby earthquakes. Thus, the precise role played by SSEs in the overall earthquake cycle is unclear. Moreover, many SSEs at convergent margins globally have been documented at the downdip limit of the seismogenic zone, i.e., at depths of 30 – 40 km (*Schwartz and Rokosky, 2007*), which makes it impossible to directly sample and study the frictional behavior of the active SSE source rocks.

The northern Hikurangi margin, offshore New Zealand, is an important example of shallow and accessible SSEs. These faults host robustly documented, quasi-periodic shallow SSEs (*Wallace, 2020*) that rupture close to the trench (*Wallace et al., 2016*) and have recurrence intervals of 12-18 months. Additionally, the source region of these SSEs has hosted tsunami earthquakes which may have ruptured to the trench (*Bell et al., 2014*) and is hypothesized to have significant pore fluid overpressure (*Bell et al., 2010; Bassett et al., 2014; Ellis et al., 2015*). Thus, it is important to constrain the frictional behavior of the source material to better understand the rock properties and processes that govern fault slip behavior, and ultimately the future risk of earthquake and tsunami generation.

Numerous studies have been undertaken in the laboratory to constrain the frictional behavior of natural fault zones (*e.g., Ikari et al., 2009; Ikari & Saffer, 2011; Carpenter et al., 2011; Carpenter et al., 2016; Ikari et al., 2020a*) and subduction inputs (e.g., *Kurzawski et al., 2016; Rabinowitz et al., 2018*). Specifically, of paramount importance are the frictional strength and the sliding stability of sheared faults. The latter quantity is usually defined within the framework of rate and state friction or RSF (*Marone, 1998*), which describes a set of constitutive equations motivated by laboratory experiments (*Dieterich, 1978, 1979; Ruina, 1983*). Broadly, laboratory observations of sliding friction can inform us about whether a fault will slide stably, resulting in aseismic creep, or unstably, giving rise to a range of slip modes including SSEs and fast dynamic earthquakes. Within this framework, SSEs arise naturally as a bridge between aseismic creep and elastodynamic ruptures based on an interaction between the fault zone elastic loading stiffness and a critical fault stiffness (*Gu et al., 1984; Leeman et al., 2016, 2018; Scuderi et al., 2017; Im et al., 2020*).

Recently, the International Ocean Discovery Program (IODP) Expeditions 372 and 375 sailed to the Hikurangi margin and sampled materials on the incoming Pacific Plate prior to subduction into the SSE region (*Barnes et al., 2019*). This provides an opportunity to sample and quantify the frictional behavior of materials likely playing an important role in hosting shallow SSEs. In particular, two distinct lithologies (chalks and phyllosilicate-rich volcaniclastic conglomerates) are abundant and likely represent a significant portion of the materials being subducted to the SSE source region based on tracing the seismic stratigraphy from the drill sites to the shallow subduction thrust (*Barnes et al., 2020*). Here, we present results from laboratory friction experiments designed to measure the frictional strength, sliding stability and healing behavior of these materials, at stresses and pore fluid pressures appropriate for conditions in the shallow SSE source area. We present results over a range of fault slip rates, from plate tectonic rates, i.e., 5 cm/yr (*Ikari et al., 2015*), to slip rates of 1 mm/s, which far exceed the peak slip rates of the shallow SSEs in the study region.

2. The Hikurangi SSEs and IODP Expeditions 372/375

The Hikurangi subduction margin accommodates westward subduction of the Pacific plate beneath the Australian plate (Figure 1a) at a rate of ~2-6 cm/yr (*Wallace et al., 2004*). A range of SSEs, with significant along-strike variations, have been documented in this region (*Wallace, 2020* and refs. therein). In particular, the northern Hikurangi SSEs are shallower (depths <15 km), marked by shorter recurrence intervals (12-18 months) and durations (2-3 weeks) (*Wallace and Beavan, 2010*), and have been documented to propagate very close to the trench (*Wallace et al., 2016*). In contrast, the deeper (25-50 km depth) SSEs at the southern Hikurangi margin are marked by longer durations (3 – 24 months) and recurrence intervals of 4-5 years (*Wallace and Beavan, 2010; Bartlow et al., 2014*). Furthermore, the source region of the northern Hikurangi shallow SSEs is interpreted to be lithologically and geometrically heterogeneous (*Barnes et al., 2020*). For example, reflection seismic surveys (Figure 1b) show that the SSE source region is broadly coincident with high reflectivity zones (*Bell et al., 2010*) inferred to be regions of high pore fluid pressure and seamount subduction (*Bell et al., 2014; Barker et al., 2018; Todd et al., 2018*). Thus, these heterogeneities have been thought to play an important role in the nucleation of shallow SSEs and the interplay between SSEs and tsunami earthquakes. However, the physical processes surrounding the origins of these diverse SSE behaviors in this region remain poorly resolved, in part, because it is not easy to directly sample the source rocks.

IODP Expeditions 372 and 375, which sailed in late 2017 and early 2018, drilled at four sites to sample the upper plate, a splay fault (near the deformation front), and the sedimentary sequence on the incoming plate (Figure 1b) at the northern Hikurangi margin, offshore Gisborne, New Zealand (*Wallace et al., 2019*). Based on reflection seismic surveys and seismic correlations with core and logging data, key lithologies involved in the source region of the shallow SSEs have been identified as lying below 510 meters below seafloor (mbsf) at site U1520 (*Barnes et al., 2020*). Specifically, marls and chalk were found at 510-849 mbsf, and the lower portion of the sediment package (below 849 mbsf) consists of a volcaniclastic facies (Figure 2). The latter material contains basalt clasts, a clay-rich (primarily saponite) altered matrix and zeolite cementation and, for a few tens of meters, carbonate-rich cementation (Figure 2; *Barnes et al., 2019; Underwood, 2020*). Data from seismic reflection surveys (e.g., *Bell et al., 2014)* and regional drilling (*Barnes et al., 2020*) point to a plate interface which is likely patchy due to the heterogeneous incoming protolith containing regionally variable thicknesses of the carbonate and volcaniclastic sediments.

While clay- (and particularly smectite) rich sediments have been documented as being weak with a tendency for velocity-strengthening frictional behavior (e.g., *Saffer and Marone, 2003; Ikari et al., 2009; Ikari & Saffer, 2011; Ujiie et al., 2013*), carbonate-rich sediments are usually significantly stronger and can exhibit velocity weakening behavior especially at elevated temperatures (*Ikari et al*., 2013; *Tesei et al., 2014; Kurzawski et al., 2016*). Field, modeling and experimental studies (eg. *Ando et al., 2010; Nakata et al., 2011; Skarbek et al., 2012; Boulton et al., 2019*) have reported that geologic and lithological heterogeneities, i.e., mixtures of velocity weakening and strengthening sediments along plate interfaces may offer one explanation for the generation of SSEs. Previous studies reporting the frictional behavior of inputs to the Hikurangi margin (*Raboniwitz et al., 2018; Boulton et al., 2019; Ikari et al., 2020a*) focused on shallower sediments (200 – 450 mbsf) farther from the trench, from Ocean Drilling Program (ODP) Site 1124, which are compositionally similar to the marls (510 – 780 mbsf) at IODP Site U1520 (Figure 2). Here, we present results from friction experiments conducted on a larger range of lithologies, and over a wider range of shearing rates and pore pressure conditions.

3. Methods

3.1. Double-direct shear experiments (0.3 - 1000 µm/s)

Biaxial experiments were conducted in a true-triaxial pressure vessel in a double direct-shear (DDS) configuration in the Penn State Rock and Sediment Mechanics Laboratory (e.g., *Samuelson et al., 2009*). In this configuration, servo-controlled horizontal and vertical pistons directly apply normal (σ) and shear stresses (τ) respectively to two gouge layers sandwiched between three steel blocks (Figure 3a). Confining (P_c) and pore fluid pressures (inflow - P_{pA} and outflow - P_{pB}) are independently servo-controlled via pressure intensifiers. Normal stress is applied on the gouge layers (30 cm^2 nominal contact area) as a load boundary condition. Shear is applied on the longer central forcing block through a prescribed loading/shearing rate, thus deforming the sandwiched gouge layers. Grooves in sintered frits ensure that deformation occurs within the gouge layers rather than localizing at the steel-gouge interface (Figure 3a) and provides spatially-uniform fluid access to the fault zone. A confining pressure (oil-based) is applied to achieve a true triaxial stress state. Rubber jackets surrounding the DDS assembly ensure that the pore fluids in the sample remain isolated from the oil-based confining pressure. In experiments where pore pressure is applied, the gouge layers are initially saturated by applying a constant pressure to the pore fluid (de-ionized water) at the inflow end, and the outflow end is connected to a vacuum pump. This ensures that the pore spaces are completely filled with the pore fluid. In our experiments, a constant pore pressure was applied on both the inflow and outflow sides during shear, keeping the sample under a drained boundary condition. While a temporarily undrained condition is possible internally in the gouge layers, past studies (*Ikari et al., 2009*) have demonstrated that significant pore pressure transients do not develop in our configuration. Previous studies have quantified that the rubber jackets have negligible strength (*Samuelson et al., 2009; Carpenter et al., 2016)*.

Normal and shear loads are measured using strain gauge load cells with a resolution of 0.1 kN. Fault normal and shear displacements are measured using direct-current linear variable differential transformers (DC-LVDTs). Confining pressure and associated volumetric changes are measured using a pressure transducer and a DC-LVDT affixed to the P_c intensifier. In the case of pore pressures, the pressure transducers are located close to the sample in order to minimize sensing volume and thus measure any small variations, whereas the displacement transducers (for measuring volumetric changes) are fixed to the P_{pA} and P_{pB} intensifiers. All pressure transducers have a measurement resolution of 7 kPa. Mechanical data are acquired continuously at 10 kHz and averaged to 100-1000 Hz in real-time for storage. All experiments were conducted at an effective normal stress (σ_{eff}) of 25 MPa, over a range of pore pressures and slip rates, from sub-slow slip rates of 0.3 μm/s (~1-3 cm/day) to 1000 μm/s. Table 1 contains the list of experiments and associated boundary conditions.

Input material sampled at four depth intervals (Figure 2) from Site U1520 were reconstituted and dried in an oven in vacuum at 40°C for 48 hours. Subsequently, the dry rocks were crushed, ground and sieved to a particle size of <125 μm. Gouge layers were constructed with a measured mass of material to ensure reproducibility and to a thickness of 5 mm width in a levelling jig (dry and under atmospheric pressure conditions). Layer thickness was measured prior to load application and at multiple points after the normal stress was applied, in order to calculate shear strains. Deionized water (DI) was used to saturate the samples since the drying process precipitates dissolved salts from the seawater into the sample. Thus, during saturation, we expect the salts to dissolve into the DI water bringing the brine concentration and chemistry back to levels that may closely resemble in-situ brine concentration.

Each experiment in the biaxial configuration consisted of a similar loading and shearing protocol. We conducted 1-2 unload/reload cycles during the first 5 mm of shear (Figure 4) to accelerate the development of a steady-state frictional behavior (*Saffer et al*., 2001; *Frye and Marone, 2002; Mair and Marone, 1999*). We followed this with a sequence of velocity steps (0.3 – 1000 μm/s) and slide-hold-slide experiments (1 – 3000 s hold times) over a displacement range of up to 25 mm (Figure 4).

3.2. Single-direct shear experiments (10^{-3} - 1 μm/s)

Low-velocity experiments were performed in a Giesa RS5 direct shear apparatus (Figure 3b) to explore the frictional behavior of the U1520 input material over a range of slip rates from plate-rate (1.6 μm/s, or 5 cm/yr) to slow-slip rates (0.5 μm/s, or 4.3 cm/day). In this experimental configuration, disaggregated gouge was mixed with DI water to create a water-saturated paste and placed in a sample cell (*Ikari et al., 2015*). The samples were sandwiched between porous steel frits at room temperature and DI water saturated conditions. The normal stress was applied vertically by vertical ram acting on a fixed top plate and the shear/loading rate was imposed by translating the base plate (Figure 3b). This forced shear to localize along a narrow zone (up to ~100s of μm thickness) as the two halves of the sample slide past each-other. Shear displacements were measured at two locations – one referenced to a horizontal, shear load cell (with resolution 0.3 kPa) measured the imposed shear displacement (or load point displacement) and another referenced to the sample measured the slip accommodated by the sample itself. The sample freely communicates with the pore fluid reservoir, and is allowed to drain to the atmosphere in order to dissipate local pore pressure development. On application of the normal load (25 MPa), the sample was allowed to consolidate and drain to the atmosphere for at least ~18 hours, until a steady state sample thickness was achieved, prior to shear. Thus, by the nature of the experimental design, pore pressures were not measured, but the sample was assumed to be under drained, zero pore pressure conditions before shearing. Additionally, because the strain rates in this configuration are extremely low, we do not expect significant excess pore pressures to develop locally in the sample.

Samples were sheared at a run-in velocity of 10 μm/s for ~4-5 mm until a steady-state friction coefficient was achieved. Subsequently, velocity step experiments were conducted over the range of 1.6 nm/s to 0.5 μm/s.

3.3. Estimation of RSF parameters

In all experiments, the coefficient of friction (or simply referred to as friction), μ, is defined as the ratio of shear stress, τ, to effective normal stress, σ_{eff}.

$$\mu = \frac{\tau}{\sigma_{eff}} \tag{1}$$

In Eq. (1), σ_{eff} is the combined effect of the applied normal stress, σ_N, the net confining pressure acting normal to the gouge layers, and the applied pore pressure, P_p, and can be represented as

$$\sigma_{eff} = (\sigma_N + 0.629P_c) - P_p \tag{2}$$

Within the framework of RSF, the velocity dependence of friction can be described as follows:

$$\mu = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b_1\ln\left(\frac{\theta_1}{\theta_{1,0}}\right) + b_2\ln\left(\frac{\theta_2}{\theta_{2,0}}\right) \tag{3}$$

In Eq. (3), *a, b_1* and b_2 are empirically determined constants, *V* is the fault slip rate, θ_1 and θ_2 are stable variables and the subscript '0' represents these quantities at an arbitrary reference state. Normally, most velocity step experiments can be well-described by a single state variable, although some velocity steps which are poorly fit by a 1-state variable RSF equation are better fit by a 2- state variable law (*Marone, 1998*) as described in Eq. (3). The RSF constants *a* and *b* are usually taken to represent some thermally-activated contact-scale Arrhenius-type process and a measure of the real area of asperity contact, respectively (*Ikari et al., 2016; Scholz, 2019*). The state variable, θ, represents contact age or contact lifetime (i.e., rapidly sliding contacts have a smaller contact age than slowly deforming contacts) and is represented as the ratio of a critical slip distance, D_c, and the asperity/contact sliding velocity. The evolution of frictional state (in a 1- or 2- state variable case) in response to a perturbation is usually expressed in one of two functional forms as the time-dependent Dieterich/aging law (*Dieterich, 1979*) or the slip-dependent Ruina/slip law (*Ruina, 1983*).

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c} \qquad \text{(Aging Law)} \tag{4}$$

$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c}\ln\left(\frac{V\theta}{D_c}\right) \quad \text{(Slip Law)} \tag{5}$$

We invert for the RSF parameters *a, b* and D_c using a least-squares procedure in RSFit3000 (*Skarbek and Savage, 2019*) by simultaneously solving Eqs. (3), and either (4) or (5) with a 1D elastic coupling equation described by

$$\frac{d\mu}{dt} = k(V_{lp} - V) \tag{6}$$

In Eq. (6), k represents the loading stiffness of the experiment and V_{lp} is the imposed shear rate. We only report values of the RSF parameters from those velocity steps where the coefficient of determination (R^2) is higher than 0.9. Thus, these inversions represent excellent fits to our experimental data. We performed RSF inversions using both the aging and slip laws for all velocity steps. However, we only report the RSF parameters from the aging law fits here since the slip law inversion consistently failed or had standard deviations greater than the mean value of the RSF parameter for higher sliding velocities. We quantify fault restrengthening by measuring frictional healing over different hold times during which the load point is held stationary (e.g., *Yasuhara et al., 2005*). We define frictional healing (*Dieterich, 1972; Beeler et al., 1994*) as the difference between peak friction upon re-shear after a hold and the previous steady state friction ($\Delta\mu_{Healing}$) (Figure 5a) and the healing rate, β, as the frictional healing per decade hold time (Figure 5b).

4. Results

4.1. Slide-Hold-Slide experiments

We observe distinctly different healing behaviors for the smectite-rich volcaniclastic facies and the chalks (Figure 5). The volcaniclastic conglomerates exhibit no post-hold peak friction upon reshear and near-zero healing rates (β = 0.0013/decade), similar to low values of frictional healing for clay-rich fault rocks and synthetic gouges reported in previous studies (e.g., *Saffer & Marone, 2003; Tesei et al. 2012;* Carpenter et al., 2012; *Carpenter et al., 2016)* for talc and montmorillonite gouges. On the other hand, the chalk lithology exhibits higher frictional healing, with healing rates (β = 0.0123/decade) (*Tesei et al., 2014*).

4.2. Velocity stepping experiments

Velocity stepping experiments allow us to define the rate-dependent friction parameter *(a-b)* and invert individually for the RSF parameters a, b and D_c (Figure 6). Our results indicate that *'a'* exhibits a modest velocity dependence (Figure 6a) while *'b'* is relatively insensitive to sliding velocity (Figure 6b). Over a range of velocities spanning plate rates (0.0016 μm/s) to faster-than-slow-slip rates (~300 μm/s), we document a bimodal behavior of friction velocity dependence (Figure 6c). Specifically, the volcaniclastic conglomerates are largely velocity neutral or slightly velocity weakening over slip rates ranging from plate-rate to slow slip rates at the northern Hikurangi margin. At ~0.3 μm/s, this behavior transitions to a steady increase in the frictional stability parameter *(a-b)* with fault slip rate for both the carbonates and the volcaniclastic facies. This form of a second-order rate dependence of friction, i.e., the rate dependence of frictional rate dependence has previously been documented in experiments conducted on a range of material including synthetic mixtures of clay minerals and quartz (*Saffer et al., 2001; Ikari et al., 2009; Kaproth and Marone, 2014*), and on natural samples from various tectonic settings (*Saito et al., 2013; Rabinowitz et al., 2018*) including those that host shallow SSEs (*Saffer and Wallace, 2015*).

The critical slip distance, D_c, shows a slip rate dependence varying as $\sim\sqrt{V}$ over the range of velocities explored (Figure 6d). Since we model some of our velocity steps with a single-state variable formulation and others with the two-state variable equation, the D_c reported in Figure 6d represents the (larger) D_{c2} for velocity steps where the 2- state variable RSF framework was used to invert our experimental data. We do so because we are interested in determining the variation of the total slip displacement required to reach a steady-state friction due to perturbations in the driving velocity, and D_{c2} is a better representative of this quantity. Few studies have documented a robust velocity dependence of D_c. However, our results closely match two cases where this velocity dependence has been documented in quartz gouge (*Mair and Marone, 1999*) and natural sediment (*Ikari et al., 2020b*) from the Waikukupa Thrust in southern New Zealand (Figure 6d). Our results demonstrating the velocity dependence of RSF parameters are consistent over a variety of hydration states (humid/saturated) and pore pressures (Figure 6c-d).

5. Discussion

Here we discuss the implications of the velocity dependence of the rate-state frictional parameters (*a, b* and D_c) in our experiments and those of others (*Mair and Marone, 1999; Ikari et al., 2020b*) for a range of different natural and synthetic fault gouges. A necessary criterion for the emergence of any kind of unstable slip in numerical simulations (*Gu et al., 1984; Im et al., 2020*) and laboratory experiments (e.g., *Leeman et al., 2016, 2018; Shreedharan et al., 2020*) is that the critical stiffness criterion be met. In other words, the fault loading stiffness (k) cannot exceed the critical rate of frictional weakening with slip (k_c) defined as

$$k \le k_c = \frac{\sigma_{eff}(b-a)}{D_c} \tag{7}$$

In the framework described by Eq. (7), slow earthquakes naturally emerge when k approaches k_c (e.g., *Liu & Rice, 2007; Leeman et al., 2016*). This criterion can also be written in terms of a critical nucleation patch size, h^* *(Dieterich, 1992)*, wherein the stiffness k is given by $k = \sim G/h^*$, where G represents a shear modulus. In this context, a larger slip patch at nucleation (h*) leads to a lower stiffness, and hence a greater tendency for instability to arise. From Eq. (7), one can observe that if the fault is velocity strengthening, i.e., *(a-b)* is positive, then the critical stiffness criterion can never be met since the positive fault stiffness can never be less than the negative critical stiffness. Thus, in this framework, a velocity strengthening fault cannot nucleate an instability or rupture unless it is strongly perturbed (*Gu et al., 1984; McLaskey and Yamashita, 2017*).

5.1. Scaling of RSF parameters with slip rate

We observe that the RSF parameters *a, b* and D_c all increase with slip rate. This indicates that for a case where $k<k_c$ such that unstable slip may initiate, k_c decreases as slip velocity grows (i.e. during the nucleation phase of an instability), thus bringing it closer to k and energetically favoring slow rupture or stable sliding rather than an elastodynamic earthquake. This has been inferred from laboratory measurements (e.g., *Ikari et al.*, 2013; *Kaproth and Marone, 2013; Saffer & Wallace*, 2015; *Leeman et al., 2016, 2018*) and demonstrated by recent numerical simulations by *Im et al. (2020)* who assume a fault with velocity dependent *(a-b)* and D_c as we document here (Figure 6). Not only does this velocity-dependence favor slow slip, it increases the range of k/k_c values where slow slip is favored (*Im et al., 2020*). Numerical models have successfully incorporated the velocity-dependence of frictional stability *(a-b)* by using a cut-off velocity (e.g., *Shibazaki and Shimamoto, 2007; Rubin, 2008*) where the fault exhibits velocity-weakening friction below the cut-off velocity and transitions to a velocity-strengthening friction above this value. In our experiments, this transitional velocity apparently coincides with the peak slip rates of the shallow SSEs documented at the northern Hikurangi margin (Figure 6c), However, this does not preclude the possibility that instabilities hosted by these lithologies far exceed this threshold velocity (*Im et al., 2020*).

5.2. Mechanisms explaining the velocity dependence of the critical slip distance, D_c

Because D_c is a parameter that is difficult to directly estimate and may only be constrained via inversion, we illustrate the velocity dependence of D_c directly by stacking multiple velocity steps with different initial velocities (Figure 7a-b). Naturally, this gives rise to questions surrounding the physical mechanisms that cause D_c to increase with slip rate. We explore dilatant strengthening and broadening of the slip zone as a candidate mechanism for the velocity-dependence of apparent or effective D_c (e.g., *Marone et al., 1990; Marone et al., 2009; Samuelson et al., 2009, 2011*), in part, because it has been suggested as a mechanism that could produce slow slip events (*Segall et al., 2010*). Dilatant strengthening is a mechanism where a rapid increase in fault zone dilation as slip rate initially increases causes a transient undrained decrease in local pore pressure, thus instantaneously increasing the local effective normal stress. As fault slip velocity increases, the fault zone dilates producing a local drop in pore pressure. This has been documented in lab studies as overprinting on the friction data by apparently increasing the D_c or the distance over which the fault achieves a new steady-state friction (*Samuelson et al., 2009, 2011*).

Based on our data showing velocity-dependent D_c in the 100% RH experiments (Figure 7b) on the volcaniclastic facies and those by *Mair and Marone (1999)* on quartz gouge at room humidity, we suggest that dilatant strengthening may not be the primary, intrinsic control on the velocity-dependence of D_c. In the case of rough, planar (or saw-cut) faults, D_c is usually defined as a microscopic asperity dimension (*Marone, 1998*). However, for our granular fault gouge with a finite volume and numerous shear fabrics (e.g., *Kenigsberg et al., 2019*), we recast D_c as the width of a localized shear zone. *Marone and Kilgore (1993)* have previously suggested this interpretation of D_c for fault gouge based on their observations of decreasing D_c with increasing shear strain, as the shear fabrics become more well-developed and deformation is increasingly accommodated in shear-parallel boundary and Y-shear fabrics.

We investigate dilatant strengthening as an additional possible mechanism by comparing velocity stepping experiments conducted in a saturated and pressurized fault to those on a fault in a 100% relative humidity environment (Figure 7a-b). We document higher values of D_c for higher sliding rates in both cases. However, while this increase is modest in the humid fault, i.e., ~10 – 75 μm for a 100x increase in loading velocity, the D_c increase is greater for the saturated fault (~40 – 250 μm for a 30x increase in loading velocity). As an additional validation exercise, we conduct velocity stepping experiments in four scenarios where the fault is pressurized to different degrees prior to shear at the same effective normal stress of 25 MPa (Figure 7c).

At higher P_P, the fault stabilizes and exhibits reduced slip weakening, lower values of the RSF parameter b and modestly higher values of D_c (Figure 7c and Supplementary Figure S1). The dependence of rate-state frictional parameters on P_P has previously been demonstrated in a limited number of studies (*Scuderi and Colletini, 2016; Xing et al., 2019; Bedford et al., 2021*). However, we note that due to the loading path (horizontal load is applied, then P_c, then P_p) in these experiments, there is also an unavoidable pre-compaction that scales with the amount of pore pressure applied. In this case, the different pre-compaction stresses would decrease the initial porosity and permeability of the fault and, by extension, dilatant strengthening to different degrees (*Samuelson et al., 2009*). Specifically, the experiment with largest pre-compaction stress (or lowest initial permeability) would experience the highest local pore pressure drop (and largest degree of dilatant strengthening) across a given velocity step. In other words, it is not possible to partition the stabilizing effects of P_P and the pre-compaction on the RSF parameters.

However, both stabilizing agents further support the possibility that dilatant strengthening is a non-trivial control on the velocity dependence of D_c.

Our results demonstrate the significant role of dilatant hardening on the 'apparent' values of RSF parameters via a competition between slip-dependent RSF parameters and time-dependent diffusion of fluids into the newly created pore spaces due to dilation. Moreover, our data are consistent with reports of dilatant strengthening on a range of gouge materials such as antigorite, olivine, quartz, chrysotile and serpentinite (*French and Zhu, 2017; Xing et al., 2019*) and direct observations of local pore-pressure drop during dynamic rupture in experimental faults (*Brantut, 2020*).

Thus, we suggest that velocity-dependent shear delocalization, and in turn, evolution of Dc, could be a significant factor in shallow SSE behavior, and future work could focus on validating/quantifying this hypothesis.

5.3.Mineralogical controls on frictional behavior

Significant lithological heterogeneities have been documented based on core sections recovered during IODP Expeditions 372/375 from Site U1520 (*Barnes et al., 2020*). Specifically, the dominant mineral types have been identified as carbonates and smectite-clays (Figure 2), occurring in the marls, chalk and volcaniclastic conglomerates. This represents an interplay of strength and frictional stability that could control the rich suite of shallow slip behaviors documented at the northern Hikurangi margin. The carbonate-rich chalk lithology is characterized by high frictional strength, high healing rates and frictional velocity-dependence spanning velocity-neutral to strengthening behaviors (Figure 8). Additionally, carbonate-bearing faults also undergo pressure solution enhanced healing at hydrothermal conditions (*Chen et al.,* *2015, 2016*) which is not fully captured in our experiments due to relatively short (maximum 3000s) hold times and room temperature conditions. Thus, we anticipate that our healing rates represent a lower bound on the potential healing that carbonates could undergo. In contrast, the deeper (>850 mbsf) smectite-rich volcaniclastic conglomerates are frictionally weak, and are velocity strengthening at slip rates over 0.1 μm/s (Figure 8). This response indicates that the frictional behavior of the clay-fractions dominates the frictional response of volcaniclastic conglomerates. Our observations are consistent with numerous studies documenting that as little as 20% (by weight) of phyllosilicate-fraction can dominate the frictional behavior of mixed gouge (*Logan and Rauenzahn, 1987; Saffer and Marone, 2003; Ikari et al., 2007; Giorgetti et al., 2015*). Finally, marls composed of ~35% phyllosilicates, 50% carbonates and 15% quartz + feldspars are characterized by an intermediate frictional response between the chalk and volcaniclastic lithologies.

We integrate our experimental measurements of healing with geodetically derived constraints from stress drop and recurrence interval of SSEs at the Hikurangi margin and seismologically estimated stress drops for a global catalog of fast earthquakes (Figure 9). Specifically, we constrain healing for ‘ordinary’ earthquakes using a global catalog of fast, elastodynamic seismicity with relatively well-resolved recurrence intervals (*Kanamori and Allen, 1986*), and estimate their stress drops from moment magnitudes using a circular crack model (*Brune, 1970*). These earthquakes represent a moment magnitude, M_w, range of 5.6-7.8 and recurrence times of the order of ~50 – 60000 years (*Kanamori and Allen, 1986*). Based on fits to the log-linear relationship between the static stress drop and recurrence times for these earthquakes, we estimate an average healing rate of ~1.6 MPa/decade. Because these earthquakes represent a range of depths and hydrothermal conditions which could control healing rates (*Carpenter et al.,* *2016*), our calculations provide a qualitative estimate of healing rates which can be compared with SSEs. However, the relatively high healing rates that we document here are consistent with earthquake nucleation in predominantly quartzofeldspathic crystalline basement (*Carpenter et al., 2012; Carpenter et al., 2016*). Our observations of the stress drop – recurrence time relationship for SSEs at the northern Hikurangi margin (*Wallace and Beavan, 2010; Bartlow et al., 2014*) low healing and small stress drops (~ 10s of kPa) for the shallow SSEs in this region. This is consistent with the low static stress-drop model of SSE nucleation (*Brodsky and Mori, 2007; Ide et al., 2007; Segall et al., 2010*) and low inferred values of stress drops associated with the northern Hikurangi SSEs (*Bartlow et al., 2014*) and SSEs globally (*Bürgmann, 2018*).

Our experimental estimates of healing (and healing rates) in the chalk and volcaniclastic facies provide depth-dependent constraints on healing rates when extrapolated to hold times consistent with the recurrence duration of the quasi-periodic shallow SSEs at the northern Hikurangi margin. Specifically, we consider two end-member scenarios to estimate maximum and minimum stress healing rates (MPa/decade) for mixtures of the subducting sediments – a carbonate-rich fault and little/no pore-fluid overpressures representing the highest healing rates, and a smectite-rich fault with significant (locally undrained) overpressures representing the lowest healing rates at an effective stress of 25 MPa. The geodetically defined healing rate (0.1 MPa/decade) is intermediate between the high healing rates (~0.31 MPa/decade) of carbonate faults and the lower healing rates (~0.03 MPa/decade) of the volcaniclastic conglomerates. Broadly, our results indicate that mixing between the strong, brittle carbonates and the weak, viscous clay minerals could be an important two-phase mineralogical control on healing and shallow SSE nucleation at the northern Hikurangi margin, consistent with structural observations by *Leah et al. (2020)*. Because the shallow portion of the northern Hikurangi margin is relatively cold (*McCaffrey et al., 2008*), we do not consider the role of temperature here, but it could be an additional control at depth, particularly downdip of the seismogenic zone.

5.4.Implications for shallow SSEs at the northern Hikurangi Margin

We present a conceptual model of subduction at the Hikurangi margin based on our observations of velocity-dependent friction and the strong mineralogical controls on frictional behavior (Figure 10). In this model, frictional (carbonates, seamounts) and geometric (seamounts) asperities on the downgoing plate are embedded in (or mix with) a viscous matrix of predominantly velocity-neutral, frictionally weak volcaniclastic conglomerates which exhibit low healing rates, indicating an inability to store elastic strain energy over long timescales. Shallow instabilities may nucleate in the strong, velocity-strengthening carbonates with high healing rates at modestly elevated temperatures and/or stresses (~70^0C; *Ikari et al., 2013; Kurzawski et al., 2016*). However, a combination of intrinsically velocity-dependent friction (i.e., velocity-dependence of *a-b* and D_c) and dilatant strengthening enhanced by potentially over-pressurized pore-fluids may arrest these instabilities, thus manifesting as shallow slow earthquakes. Shallow instabilities nucleating in the basaltic seamounts, depending on the degree of alteration experienced by the basalts (*Cox, 1990; Ikari et al., 2020c*), could also propagate as SSEs. Further, numerical models of shallow SSEs incorporating a cut-off velocity (*Shibazaki et al., 2019)* or explicit velocity dependence of friction parameters (*Im et al., 2020*) have qualitatively reproduced the range of slip behaviors documented here. At seismogenic depths (>7-10 km), pressure-temperature conditions are conducive for carbonates to be significantly velocity weakening at all slip rates (eg. *Ikari et al., 2013; Kurzawski et al., 2016*), and thus, carbonates and/or basalts may nucleate instabilities that grow to be fast, dynamic earthquakes. In such cases, dynamic weakening could dominate in the shallower velocity-neutral/strengthening sediments thus preventing the ruptures from arresting (*Di Toro et al., 2011; Faulkner et al., 2011; Aretusini et al., 2021*). Our conceptual model, motivated by experimental results indicating the strong role of the clay-rich volcaniclastic conglomerates and the second-order velocity-dependence of friction in modulating shallow slip behavior, provides insights into the mechanics of shallow SSEs at the northern Hikurangi margin.

6. Conclusions

We present a suite of friction experiments conducted on input material to the Hikurangi subduction margin recovered during IODP Expeditions 372/375. Specifically, we quantify the frictional strength, stability and healing behavior of the two dominant lithologies – carbonates and smectite-rich volcaniclastic conglomerates. We present velocity-dependent frictional parameters *(a-b)* and D_c as potentially important controls on shallow slow earthquake nucleation here. In particular, the transition in *(a-b)* from velocity-weakening to strengthening behavior with increasing velocity could act as a rate-limiting agent, and the velocity-dependent increase in D_c increases frictional stability by reducing the critical fault stiffness (or increasing the critical nucleation dimension) further favoring slower slip. Based on velocity-stepping experiments conducted on saturated and room-dry (humid) faults, we conclude that the velocity-dependence of D_c is likely due to a combination of dilatant strengthening and shear zone delocalization at higher fault slip rates. Finally, we compare experimentally determined frictional healing rates with geodetically-inferred recurrence rates to demonstrate that the shallow slow earthquakes at the northern Hikurangi margin could be hosted by a mixture of strong, brittle carbonates and weak, viscous clay-rich sediments. Our results provide additional insights and constraints into the mechanics of shallow slow slip at the northern Hikurangi margin, and set the path for future investigations into the role of frictional heterogeneities on shallow SSEs.

Table 1. List of experiments and boundary conditions

Experiment No.	Sample Name	Apparatus	Effective normal stress, σ_{eff} (MPa)	Pore pressure, P_p	Saturation state	Shear velocities (μm/s)
p5200	U1520C13R4	Biaxial	25	0	100% RH	1-1000
p5391	U1520C38R5	Biaxial	25	5	Saturated	0.3-300
p5392	U1520C28R5	Biaxial	25	5	Saturated	0.3-300
p5393	U1520C19R2	Biaxial	25	5	Saturated	0.3-300
p5419	U1520C28R5	Biaxial	25	0, 17	Saturated	0.3-1000
p5454	U1520C28R5	Biaxial	25	0	100% RH	0.3-1000
B875gds	U1520C38R2	Plate-rate	25	0	Saturated	0.00165-1.65
B984gds	U1520C19R1	Plate-rate	25	0	Saturated	0.0016-1.65

Figures

Figure 1. (a) Map of New Zealand showing the Hikurangi Trough and interface between the subducting Pacific and overlying Australian plates. The black line and red dots show the location of seismic line 05CM-04 and IODP Expedition 372/375 drill-sites respectively. Black curves on the upper plate show 50 mm slip contours from the 2014 SSE (*Wallace et al., 2016*). (b) Two-way travel time (TWTT) versus Common Depth Point (CDP) for processed seismic line 05CM-04 showing the locations of various drill sites targeted during IODP Expedition 375, the hypocenter of the 1947 Tsunami earthquake (red star) and a proposed subducting seamount at the subduction plate interface (*After Gray et al., 2019*)

Figure 2. Depth section of various lithostratigraphic units at site U1520 and bulk sediment mineralogical composition of the samples used in this study.

Figure 3. Schematic of experimental apparatuses used in this study. (a) Samples in the biaxial apparatus are sheared in a double direct-shear configuration in a true-triaxial stress state with independent inlet (PpA) and outlet (PpB) pore fluid reservoirs. Normal and shear stresses are supplied by a horizontal and vertical piston respectively. The sample rests in a pressure vessel and is separated from the surrounding confining fluid (oil) by a rubber jacket. Inset to (a) shows the powdered sample (gouge) sandwiched between three grooved steel blocks with internal plumbing for pore fluid flow. (b) Samples in the plate rate apparatus are saturated and sheared in a single direct-shear configuration with a fixed top plate and a moving base plate. A vertical piston supplies the normal load and a horizontal piston supplies the shear load.

Figure 4. A plot of friction versus loadpoint displacement for a representative experimental run shows various aspects of each experiment including unload/reload cycles to constrain initial loading stiffness, velocity step sequences and slide-hold-slide sequences. Inset to the plot shows the evolution of friction for a velocity step from 30 to 100 μm/s.

Figure 5. Friction evolution during slide-hold-slide experiments (a) and healing rates (b) in volcaniclastic conglomerates (black) and carbonates (blue) shows the significantly higher frictional healing rates in carbonates as compared to the clay-rich volcaniclastics.

Figure 6. Evolution of rate-state friction (RSF) parameters with fault initial velocity prior to an upstep for (a) RSF parameter '*a*' (b) RSF parameter '*b*' (c) the difference (*a*-*b*) which marks the fault frictional stability as velocity weakening (VW) or velocity strengthening (VS) and (d) the critical slip distance, D_c. Different colors represent different material/samples and the symbols represent biaxial (square) and plate-rate (circle) apparatuses.

Figure 7. Evolution of the critical slip distance, D_c, with fault slip rate and pore pressure in experiments conducted on the clay-rich volcaniclastic conglomerates from sample U1520 28R5. (a) Overlay of four velocity steps in experiment with P_P = 17 MPa shows that it takes more displacement for the friction to reach a post-step steady-state value for velocity steps at higher velocities. (b) Overlay of four velocity steps in experiment with 100% relative humidity (RH) shows that it takes more displacement for the friction to reach a post-step steady-state value for velocity steps at higher velocities, even with no pore fluids. (c) matrix of different velocity steps at different hydration states shows the velocity dependence of D_c and the 'evolution' effect for

all values of P_P. However, this effect is more prominent for larger P_P values likely due to dilatational hardening.

Figure 8. Variation of (a) coefficient of friction (b) healing rate and (c) frictional stability, *(a-b)* with depth at site U1520. Different colors represent different material/samples and the symbols represent biaxial (square) and plate-rate (circle) apparatuses.

Figure 9. Compilation of fault healing from slide-hold-slide experiments in this study and earthquake stress drops for the northern Hikurangi slow earthquakes (*Wallace and Beavan, 2010; Bartlow et al., 2014*) and a global catalog of fast earthquakes (*Kanamori and Allen, 1986*) shows the remarkably low healing rates for the clay-rich volcaniclastic samples tested in this study and the shallow slow earthquakes at the northern Hikurangi margin.

Figure 10. Illustrative cartoon showing summary of potential frictional and lithological controls on slow and fast earthquakes at the northern Hikurangi margin. In this view carbonate-rich patches and seamounts make up asperity patches in a velocity neutral/strengthening matrix of the abundant clay-rich volcaniclastic material at the plate interface. The volcaniclastic inputs to the plate interface at the northern Hikurangi margin are characterized by velocity-neutral friction at low slip rates transitioning to velocity strengthening friction at ~3 μm/s, velocity-dependent D_c and exhibit extremely low (or zero) healing rates. The carbonate patches are nominally velocity strengthening at high slip rates, have velocity dependent D_c and exhibit high healing rates at shallow depths consistent with the slow earthquakes. In this model, a carbonate asperity could nucleate a shallow instability whose slip rate is modulated by a combination of the inherent

velocity dependence of friction (a-b and D_c) and dilatational hardening at high pore pressures which further enhances the velocity dependence of D_c.

Acknowledgements

We thank Steven Swavely for technical assistance with the biaxial experiments. This study was supported by a US Science Support Program Schlanger Ocean Drilling Fellowship and a Post-Expedition Award to S.S., European Research Council Advance Grant 835012 (TECTONIC), the US Department of Energy grants DESC0020512 and DE-EE0008763, and the US National Science Foundation grants EAR 1520760, EAR 1547441, and EAR 1763305 to C. Marone. Experimental data used in this study can be retrieved from https://doi.org/10.5281/zenodo.5199953.

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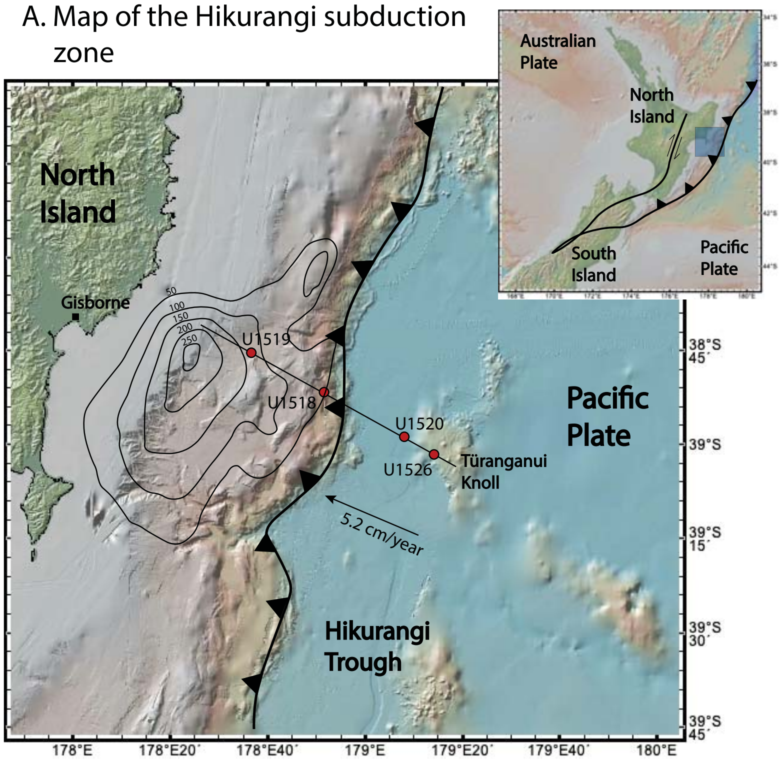
Figure 1.

A. Map of the Hikurangi subduction zone



B. Reflection seismic profile of the subdution zone (05CM-04 line)

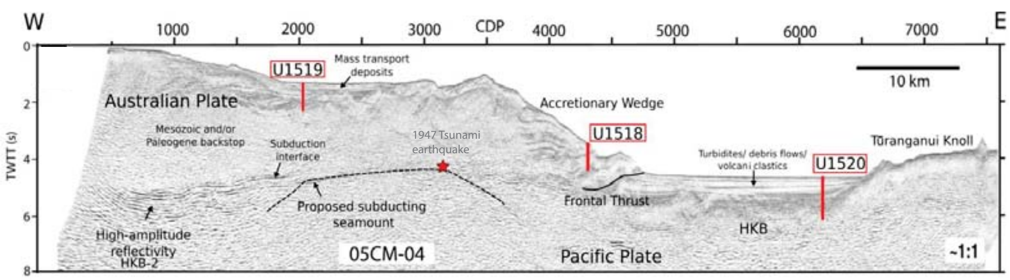


Figure 2.

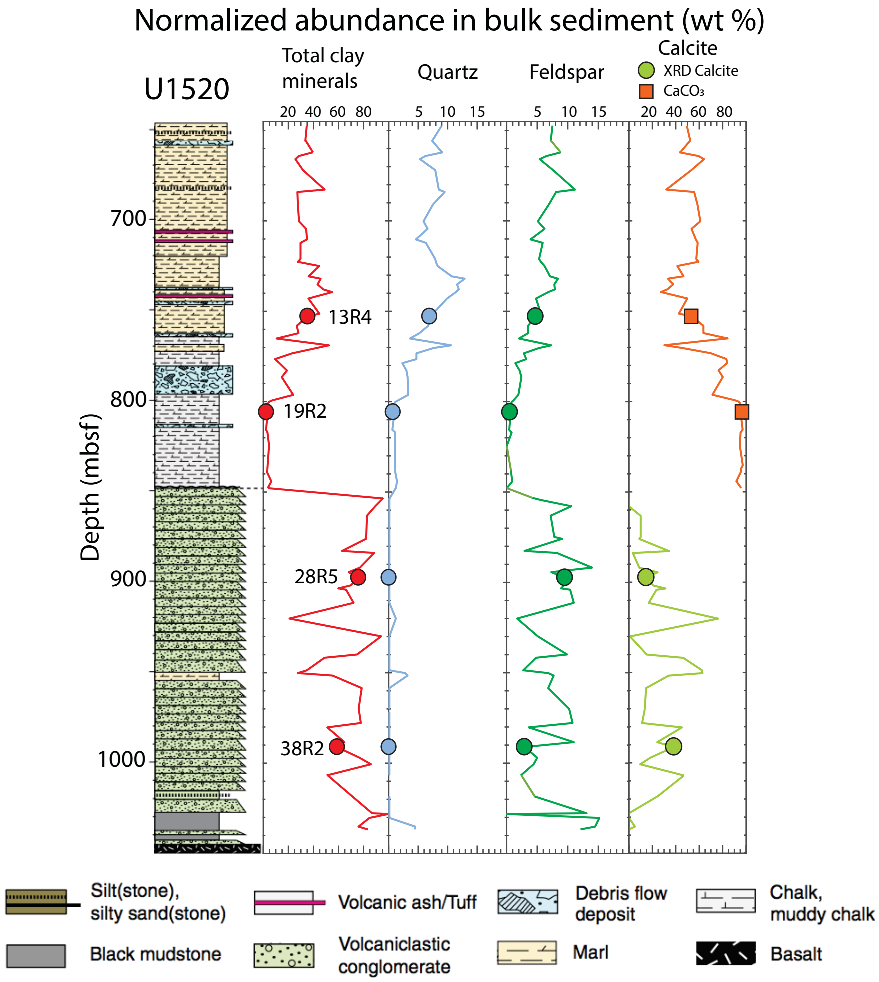

Normalized abundance in bulk sediment (wt %)
U1520
Total clay minerals
Quartz
Feldspar
Calcite
XRD Calcite
CaCO3
20 40 60 80
5 10 15
5 10 15
20 40 60 80
Depth (mbsf)
700
800
900
1000
13R4
19R2
28R5
38R2
Silt(stone), silty sand(stone)
Volcanic ash/Tuff
Debris flow deposit
Chalk, muddy chalk
Black mudstone
Volcaniclastic conglomerate
Marl
Basalt

Figure 3.

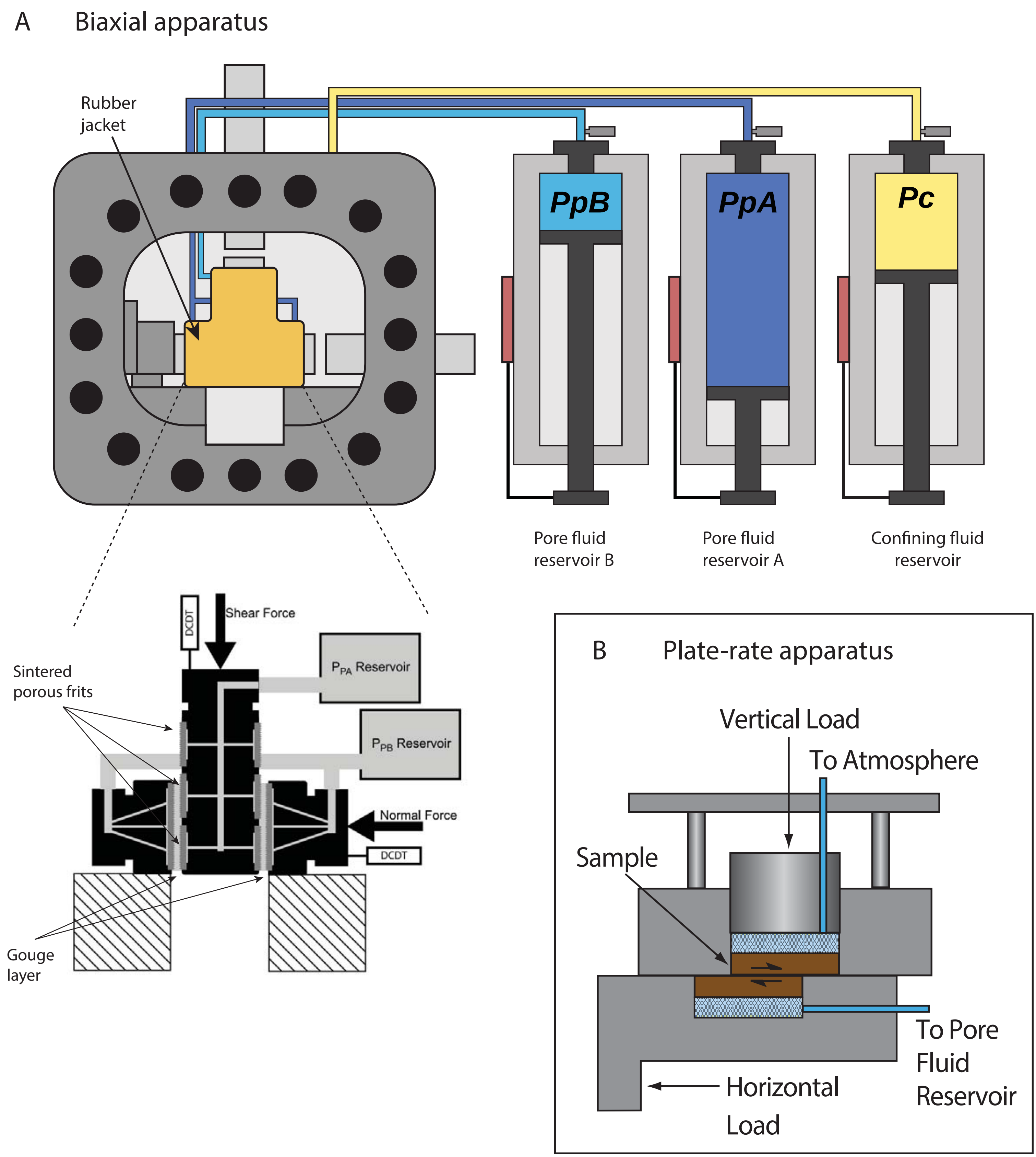
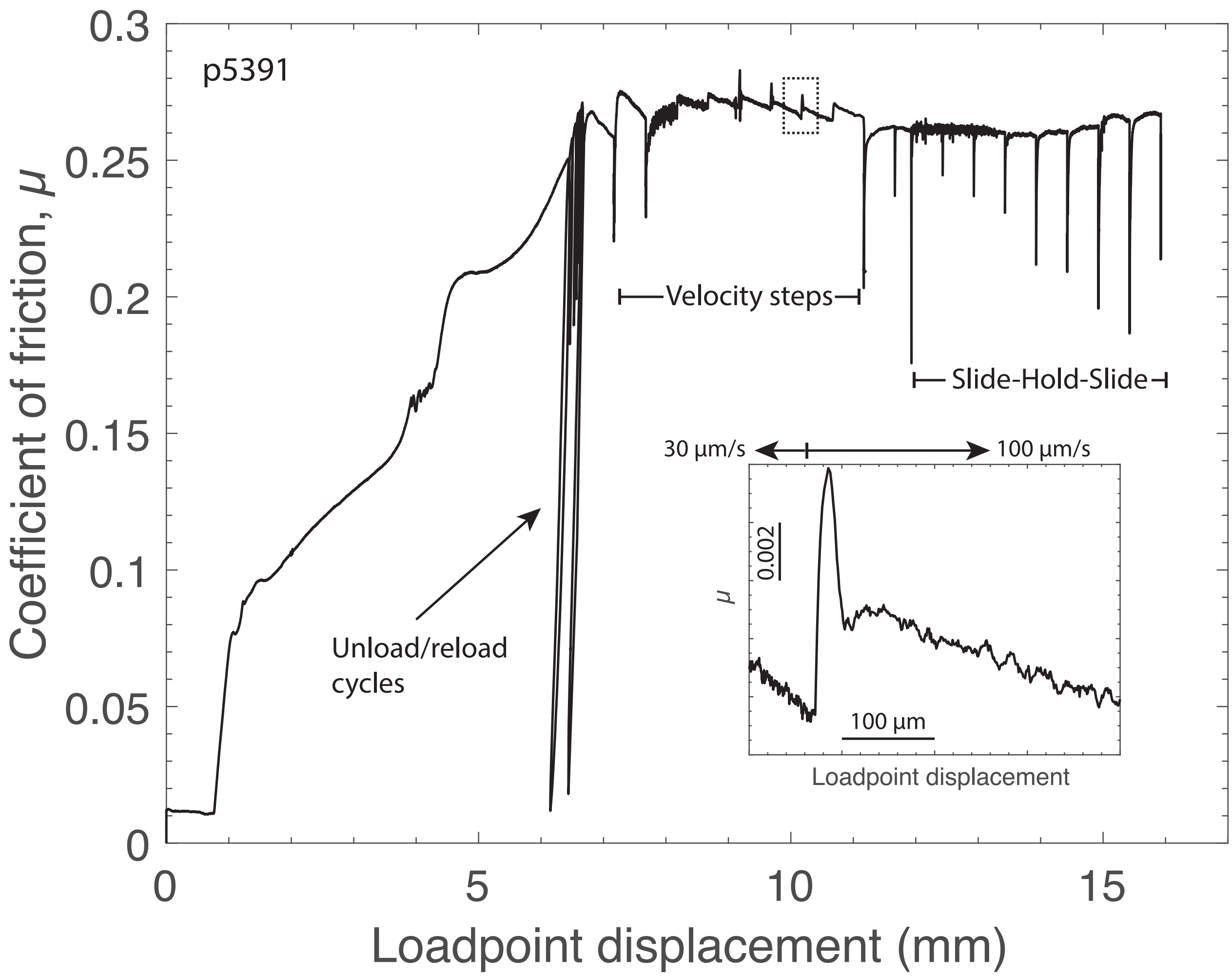
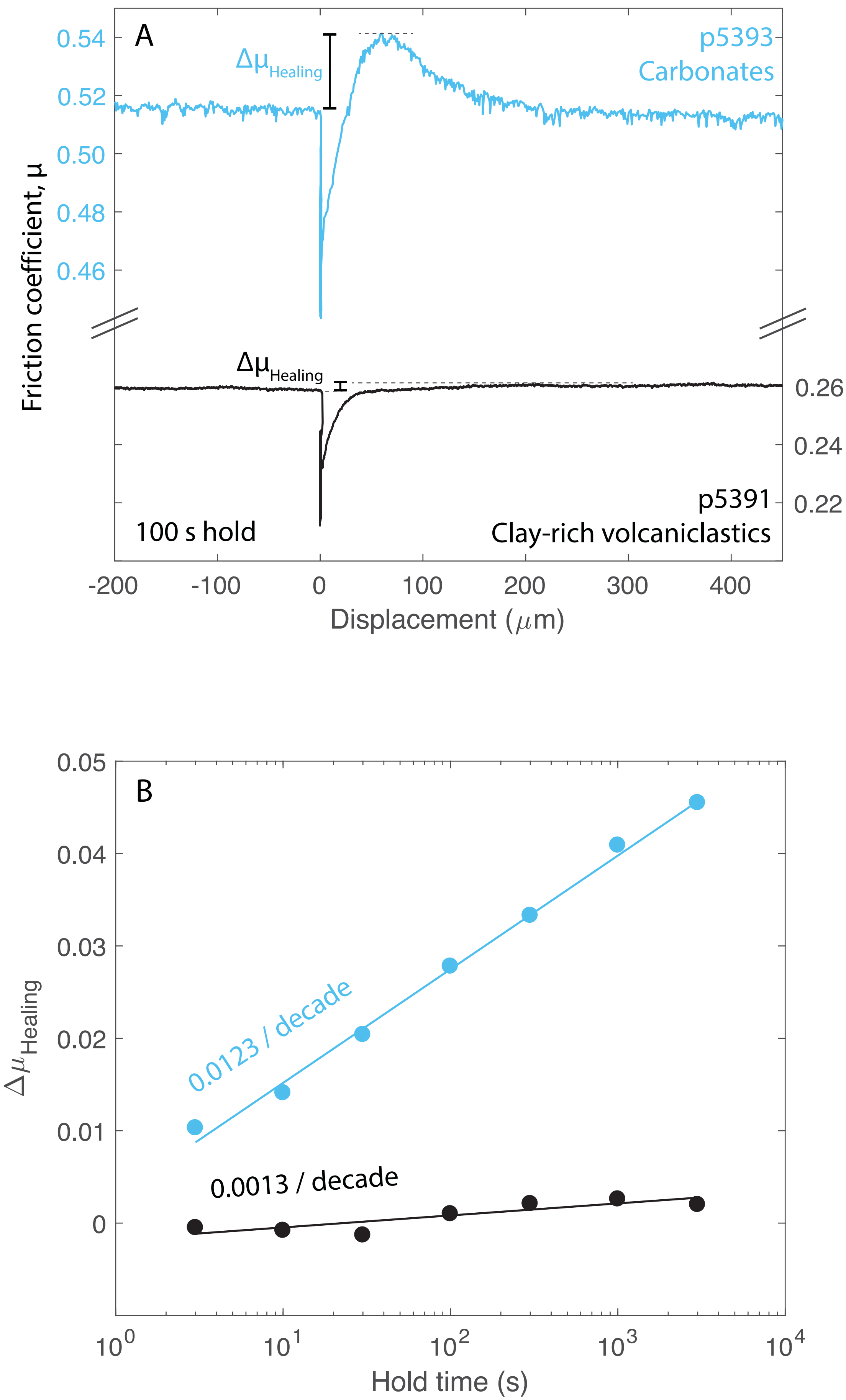

A
Biaxial apparatus
Rubber jacket
PpB
PpA
Pc
Pore fluid reservoir B
Pore fluid reservoir A
Confining fluid reservoir
DCDT
Shear Force
P_{PA} Reservoir
P_{PB} Reservoir
Sintered porous frits
Normal Force
DCDT
Gouge layer
B
Plate-rate apparatus
Vertical Load
To Atmosphere
Sample
To Pore Fluid Reservoir
Horizontal Load

Figure 4.



p5391
Coefficient of friction, μ
Loadpoint displacement (mm)
0
0.05
0.1
0.15
0.2
0.25
0.3
5
10
15
Velocity steps
Slide-Hold-Slide
Unload/reload cycles
30 μm/s
100 μm/s
0.002
μ
100 μm
Loadpoint displacement

Figure 5.



A
Δμ Healing
p5393
Carbonates
0.54
0.52
0.50
0.48
0.46
Friction coefficient, μ
Δμ Healing
0.26
0.24
0.22
p5391
100 s hold
Clay-rich volcaniclastics
-200
-100
0
100
200
300
400
Displacement (μm)
B
0.05
0.04
0.03
0.02
0.01
0
Δμ Healing
0.0123 / decade
0.0013 / decade
10^0
10^1
10^2
10^3
10^4
Hold time (s)

Figure 6.

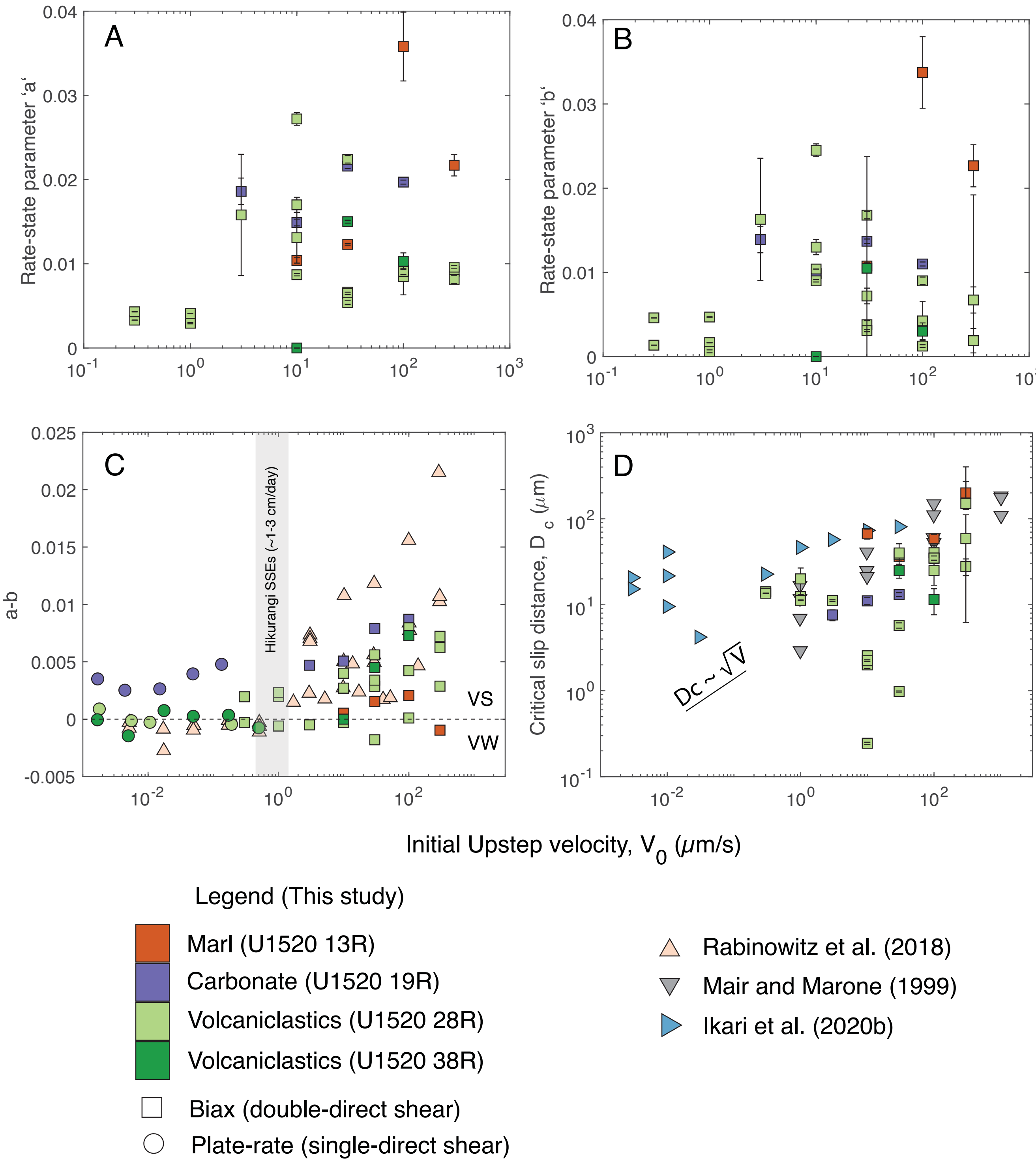
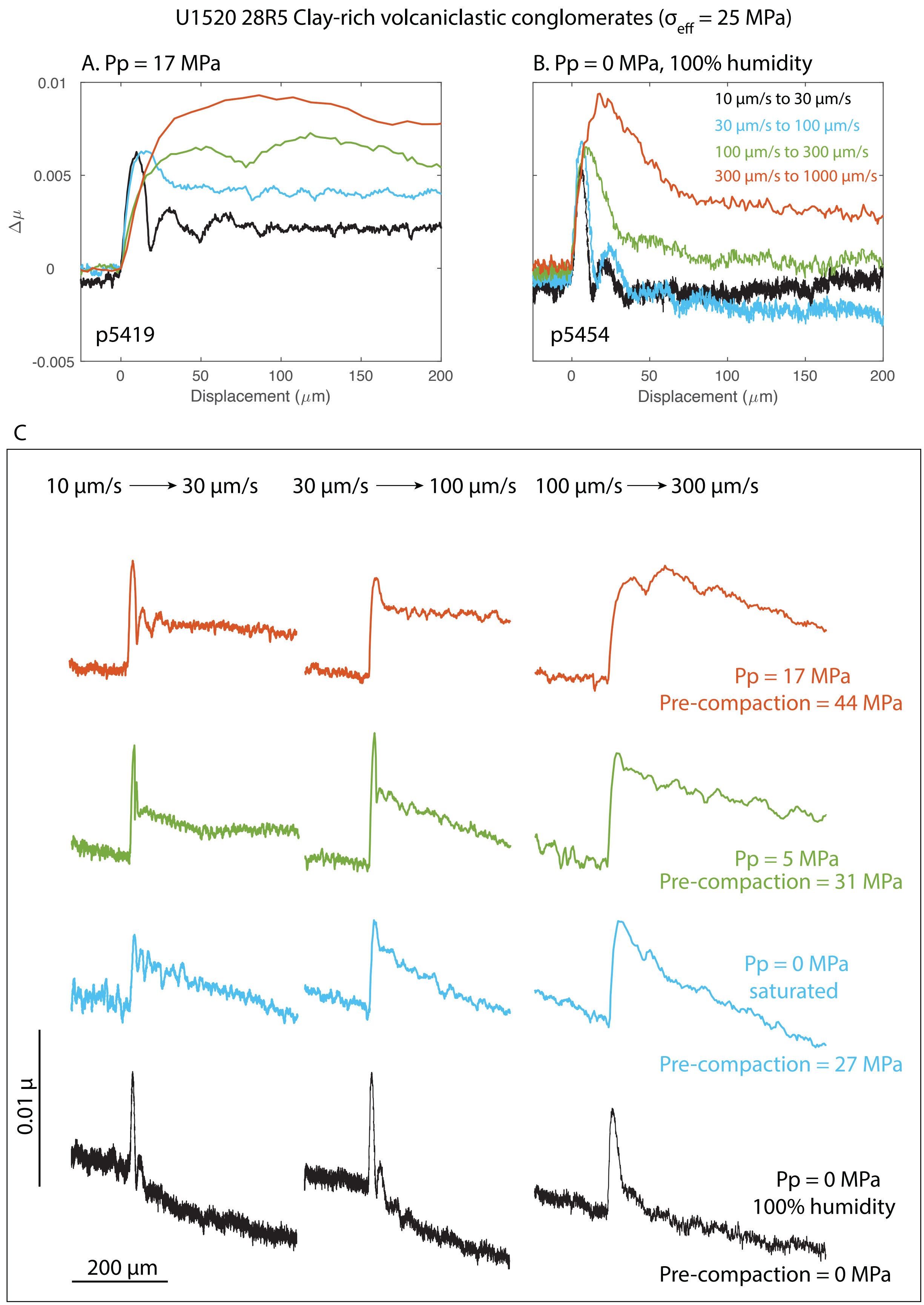
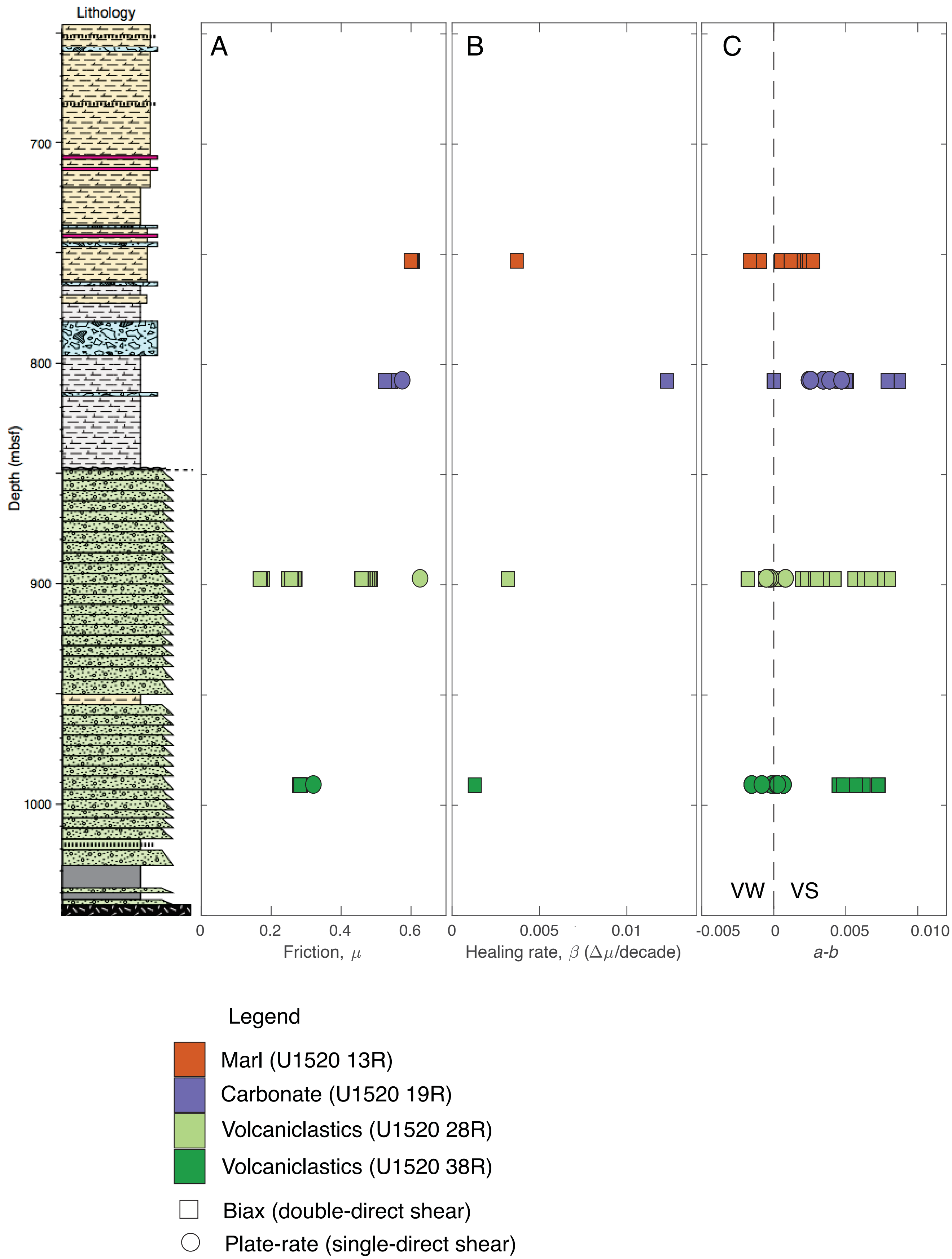

A
Rate-state parameter 'a'
B
Rate-state parameter 'b'
C
a-b
Hikurangi SSEs (~1-3 cm/day)
VS
VW
D
Critical slip distance, D_c (μm)
$Dc \sim \sqrt{V}$
Initial Upstep velocity, V_0 (μm/s)
Legend (This study)
Marl (U1520 13R)
Carbonate (U1520 19R)
Volcaniclastics (U1520 28R)
Volcaniclastics (U1520 38R)
Biax (double-direct shear)
Plate-rate (single-direct shear)
Rabinowitz et al. (2018)
Mair and Marone (1999)
Ikari et al. (2020b)

Figure 7.



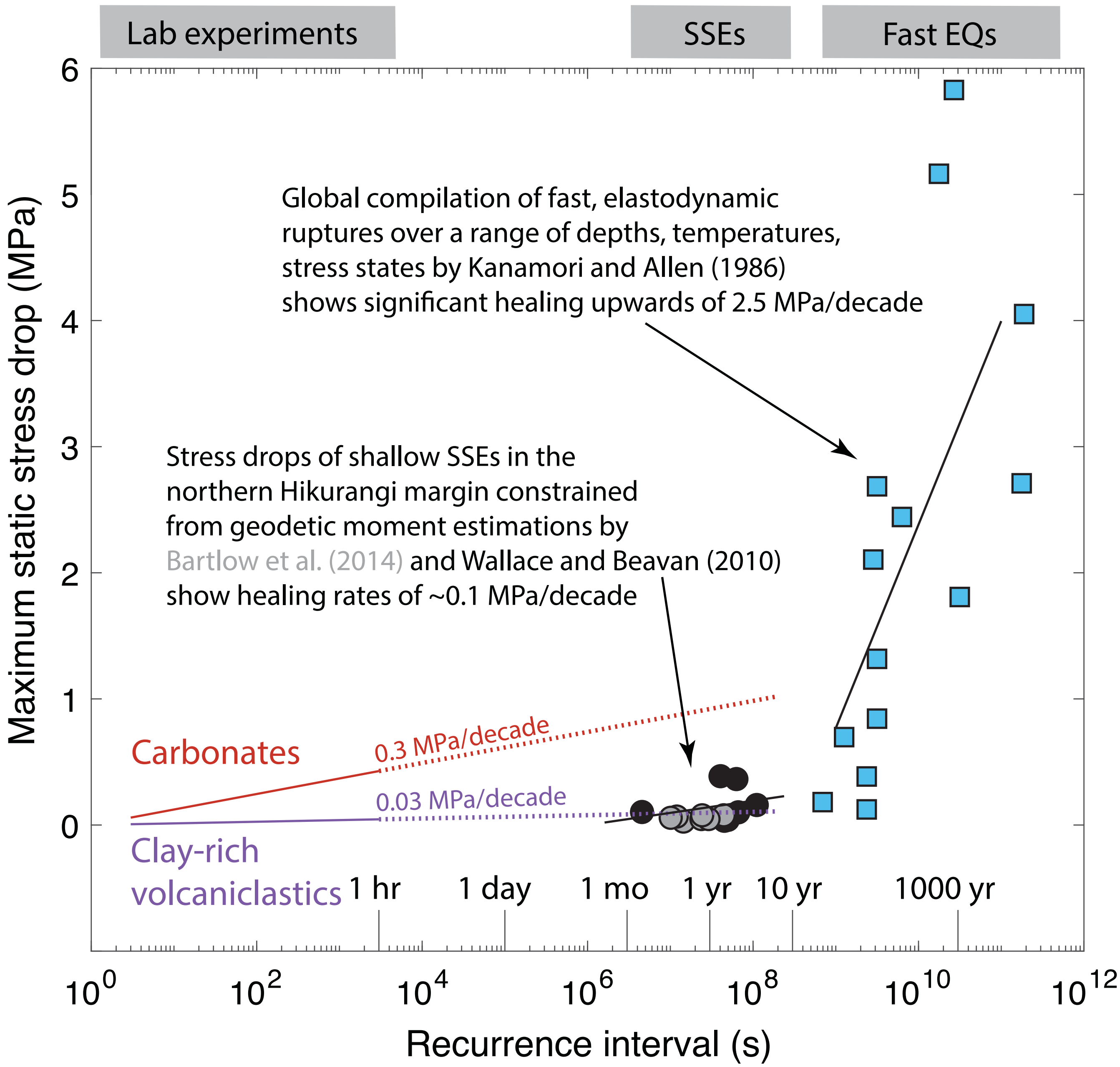
U1520 28R5 Clay-rich volcaniclastic conglomerates (σ_{eff} = 25 MPa)
A. Pp = 17 MPa
B. Pp = 0 MPa, 100% humidity
0.01
0.005
0
-0.005
Δμ
p5419
p5454
0
50
100
150
200
Displacement (μm)
10 μm/s to 30 μm/s
30 μm/s to 100 μm/s
100 μm/s to 300 μm/s
300 μm/s to 1000 μm/s
C
10 μm/s → 30 μm/s
30 μm/s → 100 μm/s
100 μm/s → 300 μm/s
Pp = 17 MPa
Pre-compaction = 44 MPa
Pp = 5 MPa
Pre-compaction = 31 MPa
Pp = 0 MPa
saturated
Pre-compaction = 27 MPa
0.01 μ
Pp = 0 MPa
100% humidity
200 μm
Pre-compaction = 0 MPa

Figure 8.



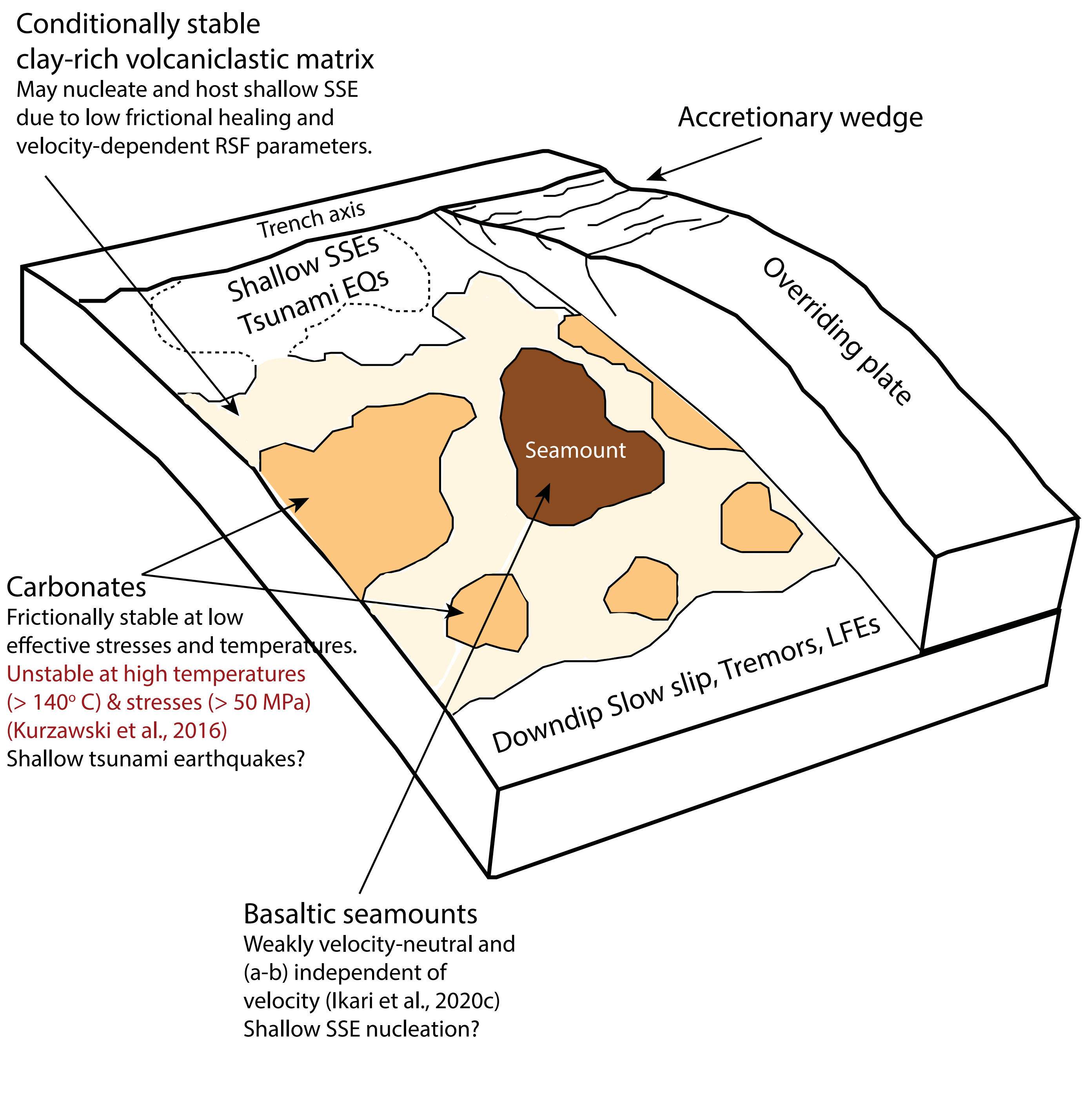
Lithology
Depth (mbsf)
700
800
900
1000
A
B
C
VW
VS
0
0.2
0.4
0.6
Friction, μ
0
0.005
0.01
Healing rate, β ($\Delta\mu$/decade)
-0.005
0
0.005
0.010
a-b
Legend
Marl (U1520 13R)
Carbonate (U1520 19R)
Volcaniclastics (U1520 28R)
Volcaniclastics (U1520 38R)
Biax (double-direct shear)
Plate-rate (single-direct shear)

Figure 9.



Lab experiments
SSEs
Fast EQs
Global compilation of fast, elastodynamic ruptures over a range of depths, temperatures, stress states by Kanamori and Allen (1986) shows significant healing upwards of 2.5 MPa/decade
Stress drops of shallow SSEs in the northern Hikurangi margin constrained from geodetic moment estimations by Bartlow et al. (2014) and Wallace and Beavan (2010) show healing rates of ~0.1 MPa/decade
Carbonates
0.3 MPa/decade
0.03 MPa/decade
Clay-rich volcaniclastics
1 hr
1 day
1 mo
1 yr
10 yr
1000 yr
Maximum static stress drop (MPa)
Recurrence interval (s)
0
1
2
3
4
5
6
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}

Figure 10.


Conditionally stable
clay-rich volcaniclastic matrix
May nucleate and host shallow SSE
due to low frictional healing and
velocity-dependent RSF parameters.
Accretionary wedge
Trench axis
Shallow SSEs
Tsunami EQs
Overriding plate
Seamount
Carbonates
Frictionally stable at low
effective stresses and temperatures.
Unstable at high temperatures
(> 140° C) & stresses (> 50 MPa)
(Kurzawski et al., 2016)
Shallow tsunami earthquakes?
Downdip Slow slip, Tremors, LFEs
Basaltic seamounts
Weakly velocity-neutral and
(a-b) independent of
velocity (Ikari et al., 2020c)
Shallow SSE nucleation?