Effects of smectite to illite transformation on the frictional strength and sliding stability of intact marine mudstones

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[1] At subduction zones, earthquake nucleation and coseismic slip occur only within a limited depth range, known as the "seismogenic zone". One leading hypothesis for the upper aseismic-seismic transition is that transformation of smectite to illite at ∼100–150°C triggers a change from rate-strengthening frictional behavior that allows only stable sliding, to rate weakening behavior considered a prerequisite for unstable slip. Previous studies on powdered gouges have shown that changes in clay mineralogy alone are unlikely to control this transition, but associated fabric and cementation developed during diagenesis remain possible candidates. We conducted shearing experiments designed specifically to evaluate this hypothesis, by using intact wafers of mudstone from Ocean Drilling Program Site 1174, offshore SW Japan, which have undergone progressive smectite transformation in situ. We sheared specimens along a sawcut in a triaxial configuration, oriented parallel to bedding, at normal stresses of ∼20–150 MPa and a pore pressure of 1 MPa. During shearing, we conducted velocity-stepping tests to measure the friction rate parameter (*a-b*). Friction coefficient ranges from 0.28–0.40 and values of (*a-b*) are uniformly positive; both are independent of clay transformation progress. Our work represents the most direct and comprehensive test of the clay transformation hypothesis to date, and suggests that neither illitization, nor accompanying fabric development and cementation, trigger a transition to unstable frictional behavior. We suggest that strain localization, in combination with precipitation of calcite and quartz, is a viable alternative that is consistent with both field observations and recent conceptual models of a heterogeneous seismogenic zone. **Citation:** Saffer, D. M., D. A. Lockner, and A. McKiernan (2012), Effects of smectite to illite transformation on the frictional strength and sliding stability of intact marine mudstones, *Geophys. Res. Lett.*, *39*, L11304, doi:10.1029/2012GL051761.

1. Introduction

[2] At subduction zones the plate boundary typically localizes within fine-grained marine sediments from the incoming oceanic plate [e.g., *Moore et al.*, 2001, 2007; *Kimura et al.*, 2012]. The subduction megathrust is generally divided into three regions: (1) an upper aseismic zone; (2) a seismogenic zone that is interseismically locked, capable of nucleating earthquakes, and slips coseismically; and (3) a downdip aseismic region [e.g., *Hyndman et al.*, 1997]. Recent work suggests that this view is probably oversimplified [e.g., *Lay and Bilek*, 2007], because slip transients have been documented in the presumed aseismic updip region, including very low frequency earthquakes (VLFE) and tectonic tremor [e.g., *Ito and Obara*, 2006], and because slip behavior and locking within the seismogenic zone are highly heterogeneous at many subduction margins due to basement relief or variations in fault zone architecture [e.g., *Wang and Bilek*, 2011]. In some cases, such as the recent Mw 9.0 Tohoku earthquake, coseismic slip continues to the trench, suggesting that large ruptures can propagate into conditionally stable shallow portions of the megathrust [*Lay and Kanamori*, 2011; *Faulkner et al.*, 2011].

[3] The fault rock properties, composition, and in situ conditions that control slip behavior along subduction megathrusts remains a major unresolved question, with important implications for understanding (1) the width and size of regions that may slip coseismically, and (2) the underlying causes of different modes of fault slip [e.g., *Moore and Saffer*, 2001; *Lay and Kanamori*, 2011]. The updip edge of the seismogenic zone at many subduction margins, as defined on the basis of interseismic locking, the distribution of coseismic slip, and the distribution of well-located microseismicity, occurs at an estimated temperature of 100–150°C [e.g., *Oleskevich et al.*, 1999]. This temperature range coincides with a range of diagenetic and low-grade metamorphic processes that are hypothesized to modify sediment properties and ultimately allow unstable slip [e.g., *Moore and Saffer*, 2001; *Saffer and Marone*, 2003].

[4] One leading hypothesis to explain this updip limit is the transformation of smectite to illite clay, which reaches completion by ∼120–150°C and is accompanied by release of structurally bound water [e.g., *Vrolijk*, 1990]. This idea is consistent with a limited number of experiments that have documented stick-slip behavior in heated illite gouge [*Moore et al.*, 1989]. However, several recent studies have shown that increased illite abundance in remolded or powdered clay-rich experimental fault gouges does not substantially affect frictional strength [*Brown et al.*, 2003; *Kopf and Brown*, 2003] or trigger a transition to velocity weakening frictional behavior, which is a prerequisite for unstable slip [*Saffer and Marone*, 2003; *Ikari et al.*, 2009]. Some studies have shown that increased illite content leads to more pronounced rate-strengthening, opposite to that expected if the transformation to illite indeed controls the onset of seismogenesis [e.g., *Tembe et al.*, 2010].

[5] However, existing work has explored only a limited range of stress conditions, saturation states, and materials,

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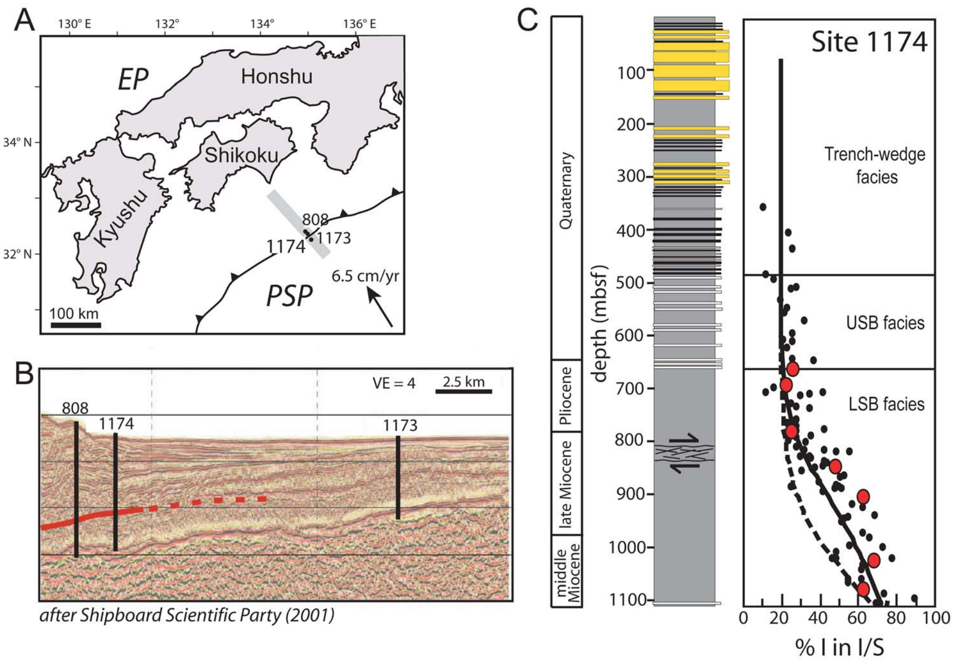

Figure 1. (a) Location map. PSP = Philippine Sea Plate; EP = Eurasian Plate. (b) Seismic line showing the décollement (red) and locations of ODP drillsites. (c) Summary of data from Site 1174. Graphic stratigraphic column follows *Shipboard Scientific Party* [2001] and *Moore et al.* [2001] (gray = mudstone; yellow = sandy turbidites; white = silt turbidites; black = ash). Right panel shows composition of interlayered I/S clays down-section (black dots), modeled clay reaction progress [after *Saffer et al.*, 2008]; black and dashed curves), and the samples used in this study (red).

leaving several key questions unanswered. Specifically, the role of intact in situ rock fabric has emerged as an important control on fault strength and slip behavior [e.g., *Collettini et al.*, 2009], yet existing studies have been conducted primarily on powdered gouge [e.g., *Brown et al.*, 2003; *Tembe et al.*, 2010]. In addition, a number of studies aimed at the frictional properties of these clays used synthetic materials [e.g., *Saffer and Marone*, 2003; *Moore and Lockner*, 2007], or were conducted under unsaturated conditions without active control of pore fluid pressure [e.g., *Saffer and Marone*, 2003]. For the latter, it is unclear whether transient fluid overpressures develop during shearing at high effective normal stresses due to the expulsion of clay interlayer water [e.g., *Moore and Lockner*, 2007]. These studies have concluded that although the change in clay mineral composition itself is unlikely to trigger a transition to unstable slip, SiO_2 cementation, consolidation, and fabric development that accompany the in situ clay transformation remain potential causes [e.g., *Marone and Scholz*, 1988; *Ikari et al.*, 2007; *Moore et al.*, 2007].

[6] Here, we address these shortcomings in order to more directly and completely test the hypothesis that smectite transformation triggers the upper transition from stable to unstable slip. We accomplish this by conducting shearing experiments on intact wafers of marine sediment from the Nankai Trough offshore SW Japan, which have undergone progressive smectite-to-illite transformation in situ (Figure 1). We substantially advance on previous work by (1) explicitly incorporating the effects of in situ illitization *and* concomitant in situ fabric development and cementation; (2) systematically investigating the effects of clay transformation on frictional strength and rate dependence over a range of effective normal stresses and sliding rates; and (3) conducting our experiments under saturated conditions and at sufficiently slow rates to ensure controlled pore fluid pressure. This represents the most direct and geologically relevant test of the clay transformation hypothesis to date.

2. Experimental Samples and Geologic Setting

[7] The Nankai accretionary complex is formed by subduction of the Philippine Sea Plate (PSP) beneath the Eurasian Plate (EP) along the Nankai Trough (Figure 1). This region has been studied extensively through geophysical surveys and several Ocean Drilling Program (ODP) cruises [e.g., *Moore et al.*, 2001, 2009]. Boreholes drilled during ODP Legs 131 and 190 include Sites 808 (~3 km arcward of the deformation front), 1174 (~2 km arcward), and 1173 (~10 km seaward) [*Moore et al.*, 2001] (Figure 1). Sites 1174 and 808 penetrated the accretionary wedge, plate boundary décollement, and underthrusting sediment section; Site 1173 sampled the sedimentary section of the incoming PSP (Figure 1). Along the drilling transect, the décollement localizes within the Miocene to Lower Pliocene Lower Shikoku Basin (LSB) Facies, which comprises a ~400 m-thick monotonous hemipelagic mudstone section [*Shipboard Scientific Party*, 2001] (Figure 1b). Due to high heat flow in this area (~180 mW m^{-2} on the PSP), temperatures reach ~140°C at the base of Sites 1174 and 808, and are sufficiently high to drive smectite-to-illite transformation at depths of 700–1100 m (Figure 1c) [*Steurer and Underwood*, 2003; *Saffer et al.*, 2008].

[8] We selected and tested a suite of 7 samples obtained from Site 1174, where the clay reaction has progressed from an initial condition of ~20% illite in interlayered illite-smectite (I/S) above ~700 mbsf, to ~80% at the base of the

Table 1. Samples Used in Our Experiments

Sample	Depth (mbsf)	% Clay[a]	% I in Mixed Layer I/S[a]
1174-55R	660.35	45	25
1174-57R	688.07	49	21
1174-67R	777.24	53	25
1174-74R	843.30	47	48
1174-80R	902.00	56	61
1174-92R	1022.18	54	67
1174-98R	1072.00	48	61
illite shale[b]	n/a	68	100

[a]Clay mineralogy data from *Shipboard Scientific Party* [2001] and *Steurer and Underwood* [2003].
[b]Commercially obtained illite shale (Rochester Shale) [*Saffer and Marone*, 2003].

hole (Figure 1c and Table 1). Experiments on this suite of natural samples provides a direct, systematic test of the role in situ clay transformation plays in governing frictional strength and stability. Moreover, by using intact wafers of preserved core, our tests explicitly incorporate both the in situ clay reaction and any associated cementation and fabric development that accompany it as part of early diagenesis.

3. Experimental Methods

[9] We selected our samples from whole-round cores, which were preserved in plastic core liners and stored in a high humidity refrigerator at 4°C (in order to maintain saturation with original formation pore fluids) until the samples were trimmed for our experiments (Figure 1c and Table 1). The samples are uniformly clay-rich (45–58 wt%), with illite abundance in I/S ranging from 21% to 67% [*Steurer and Underwood*, 2003; *McKiernan et al.*, 2005] (Table 1). For each shearing experiment, we cut intact, rectangular wafers (1–6 mm thick × 19 mm × 38 mm) from the core using a trimming jig. We cut all samples parallel to depositional fabric and to the expected shearing direction along the décollement (Figure 1b). For comparison, we also tested a commercially obtained illite shale, which we powdered and sieved to <500 μm (Table 1), and built into a 1 mm-thick layer. We sheared the samples along a 30-degree saw-cut between roughened prismatic forcing blocks of Berea Sandstone and Westerly Granite in a triaxial vessel, with the assembly sealed in shrink tubing and polyeurethane jacketing (Figure 2a) [e.g., *Tembe et al.*, 2010]. We ran all tests at room temperature, with a controlled pore fluid pressure of 1 MPa.

[10] Each sample was sheared at effective normal stresses of ~20, ~50, ~120, and ~150 MPa, to total displacement of 10 mm, corresponding to shear strains of 1.7–10 depending on initial sample thickness. We conducted velocity steps at each normal stress to measure the friction rate parameter (*a-b*), over a range of sliding velocities from 0.005 to 5 μm/sec (Figure 2b). We define the friction coefficient (μ) at the final (largest) strain at each normal stress by dividing shear stress by the effective normal stress, under the assumption that cohesion in the porous sediment and powdered gouge is negligible, and accounting for the jacket strength, changing contact area with continued displacement, and friction along the Teflon shim [*Tembe et al.*, 2010]. We define the friction rate parameter by: $(a\text{-}b) = \Delta\mu/\ln(V/V_o)$, where $\Delta\mu$ is the change in steady state friction for a given velocity step, and V and V_o are the final and initial sliding velocities. Positive values of (*a-b*) indicate that friction increases with sliding velocity and are characteristic of stable sliding behavior, whereas negative values of (*a-b*) indicate slip-weakening behavior and are a prerequisite for the nucleation of unstable slip [e.g., *Marone*, 1998].

4. Results

[11] Friction coefficients (μ) for our samples range from 0.24 to 0.40, and do not vary systematically as a function of clay transformation or effective normal stress (Figures 3a and 3b). However, our data do define a subtle decrease in friction with increasing depth and in situ temperature, from values of μ = 0.37–0.40 at 660 mbsf (~90ºC) to μ = 0.28–0.34 at 1072 mbsf (~136ºC). The values we report are consistent with friction coefficients of ~0.2–0.4 reported for

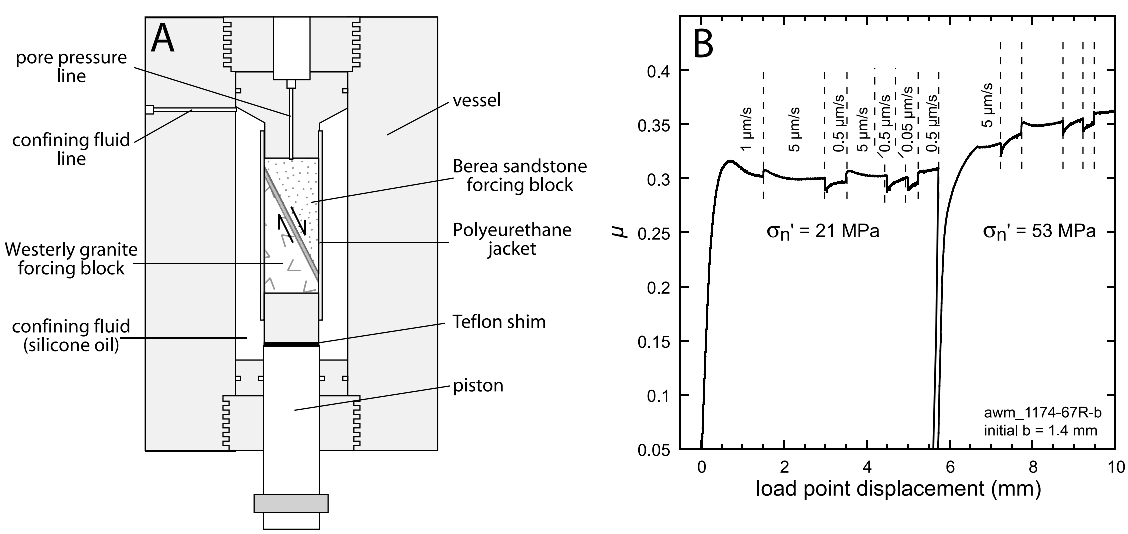

Figure 2. (a) Schematic of triaxial vessel and testing configuration. (b) Example experimental result showing friction vs. displacement for two effective normal stresses, with velocity steps as noted. Velocity stepping procedure was identical for all experiments. For the second part of the experiment shown in Figure 2b, velocity was stepped as follows after a "run-in" at 5 μm/s: 0.5 μm/s – 5 μm/s – 0.5 μm/s – 0.05 μm/s – 0.5 μm/s.

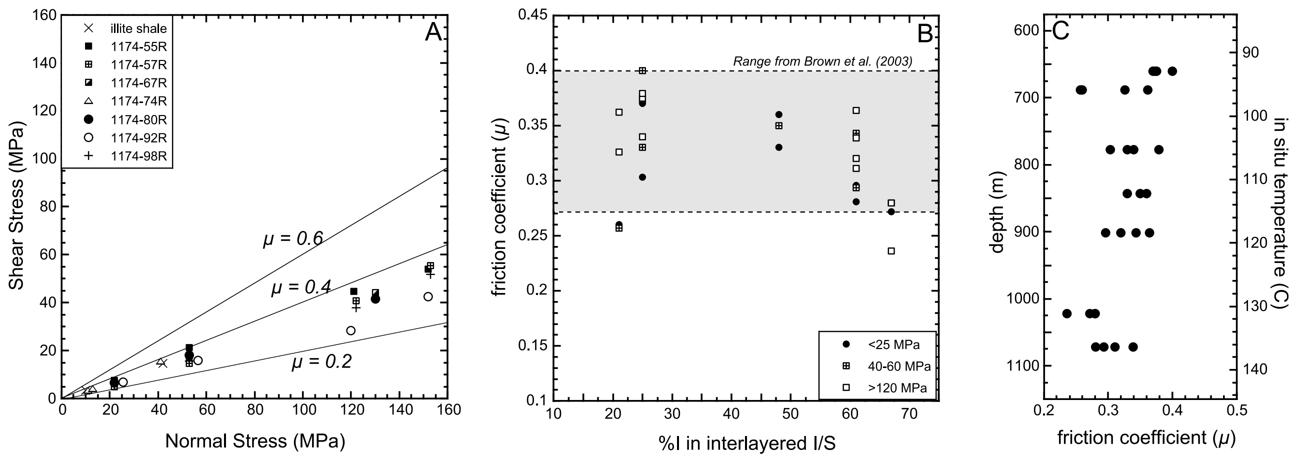

Figure 3. (a) Experimentally determined shear failure criteria for our samples. (b) Friction coefficient (μ) as a function of clay reaction progress, defined by the abundance of illite in interlayered I/S. The range of μ reported by *Brown et al.* [2003] is shown for reference (gray shaded area). (c) Friction coefficient as a function of sample depth and in situ temperature, shown for all normal stresses.

mudstones, clay standards, and clay-rich gouges in previous studies [e.g., *Morrow et al.*, 1992; *Brown et al.*, 2003; *Saffer and Marone*, 2003; *Moore and Lockner*, 2007; *Tembe et al.*, 2010] (cf. Figure 3), and with values of $\mu = \sim$0.27–0.4 reported by *Ikari and Saffer* [2011] for samples from Site 1174. *Ikari and Saffer* [2011] also noted a possible trend of decreasing friction with depth based on a limited number of experiments, which were conducted on powdered and intact wafers, and at only a single effective stress of 25 MPa. Our data are also consistent with the results of *Brown et al.* [2003], who showed that for powdered samples deformed in rotary shear, total clay content is a first-order control on μ, whereas the relative amounts of smectite and illite within the clay component are less important.

[12] Values of (*a-b*) are uniformly positive, ranging from 0.0015 to 0.013, and exhibit no systematic change with progressive smectite transformation (Figure 4a), or with increased depth or in situ temperature (Figure 4b). The friction rate parameter is also independent of effective normal stress (Figure 4) and sliding velocity (not shown) over the range of experimental conditions we investigated. These results are generally consistent with previous work on these sediments at an effective stress of 25 MPa, which reported consistently positive values of (*a-b*) ranging from 0.0001 – 0.006 [*Ikari and Saffer*, 2011].

5. Implications for Processes Controlling the Shallow Aseismic-Seismic Transition

[13] Our friction experiments were specifically designed to further test the long-standing hypothesis that the onset of subduction zone seismicity is controlled by the smectite-to-illite

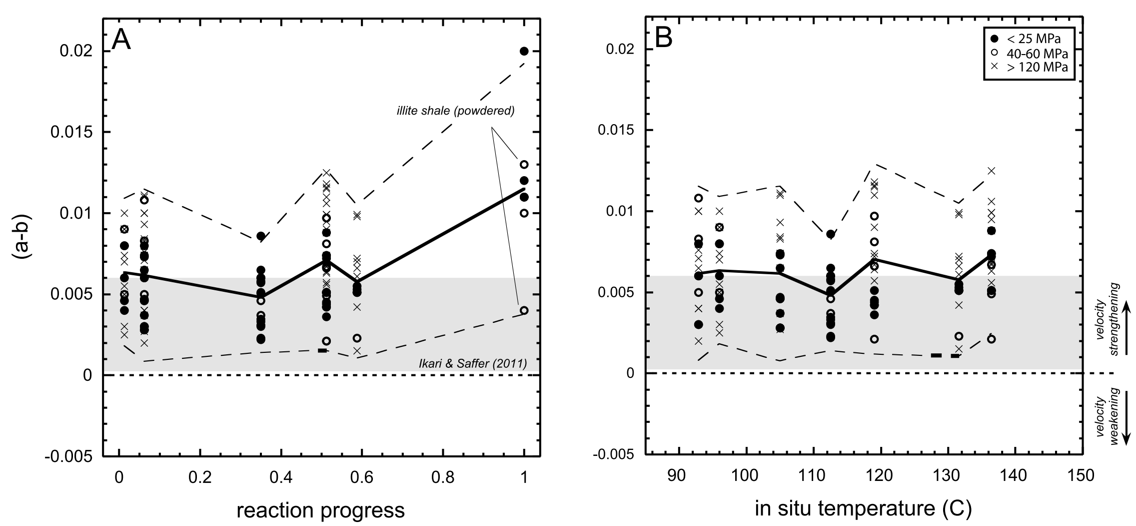

Figure 4. Friction rate parameter (*a-b*) as a function of (a) smectite-to-illite transformation progress, and (b) estimated in situ temperature. Solid lines show mean values, and dashed lines show 2 standard deviations from the mean. Range of data from *Ikari and Saffer* [2011] is shown for comparison (gray box). We observe no systematic variation in the velocity dependence of friction with progressive clay transformation or with in situ temperature, suggesting that neither illitization nor fabric development within the mudstone associated with compaction, cementation and recrystallization trigger a transition to unstable or conditionally stable frictional behavior.

transformation. We used intact samples of natural hemipelagic mudstones from the Nankai Trough, which have undergone burial diagenesis and *in situ* clay transformation (cf. Figure 1c). These samples are ideal analogs for the material within the subduction megathrust; furthermore, by testing intact wafers of material, our experiments capture - for the first time - both the clay mineral transformation itself *and* the associated changes in rock fabric and cementation that have occurred during in situ burial diagenesis. Our study also significantly extends previous work by exploring a larger range of normal stresses and saturation states, and by addressing unresolved experimental issues from previous testing programs [e.g., *Saffer and Marone*, 2003] (i.e., by controlling sample drainage state).

[14] Our primary result is that both the friction coefficient (μ) and the friction rate parameter (*a-b*) are independent of clay reaction progress (Figures 3 and 4). This provides the most comprehensive and direct test of the clay transformation hypothesis to date, and suggests that illitization itself does not, in fact, trigger a transition to unstable or conditionally stable frictional behavior of the subduction plate interface. Although detailed characterization of the sediment fabric as a function of burial depth and clay transformation is beyond the scope of this study, our results effectively rule out the idea that in situ cementation and fabric development accompanying clay recrystallization – both of which are preserved in our intact wafers - drive a transition in frictional velocity-dependence as posited on the basis of previous studies on powdered gouge [e.g., *Saffer and Marone*, 2003; *Ikari et al.*, 2007]. The trend of decreasing friction coefficient (μ) with depth and in situ temperature indicates that although it does not affect the friction rate parameter, the intact rock fabric may have an effect, albeit small, on frictional strength [e.g., *Ikari and Saffer*, 2011].

[15] By ruling out the role of lithification processes in the mudstone matrix that accompany illitization, such as Si cementation, growth and recrystallization of clays, and associated fabric development, our results further narrow the range of processes that could trigger a change in rock frictional properties and ultimately drive a transition from stable sliding near the trench to conditionally stable or unstable frictional behavior at greater depths. It is important to note that our room-temperature experiments cannot rule out the role of thermally activated processes, such as pressure solution or further dehydration reactions, which could lead to velocity-weakening behavior at temperatures $>\sim 200°C$, and may not require a specific mineral transformation [e.g., *den Hartog et al.*, 2012; *Blanpied et al.*, 1995]. Chemically-assisted weakening and evolution of frictional rate dependence along subduction zone faults is also hypothesized to control slip behavior at greater depths, for example due to phyllosilicate transformation to muscovite [e.g., *den Hartog et al.*, 2012], and serpentinization and talc formation [e.g., *Hyndman et al.*, 1997].

[16] One alternative process to explain the frictional transition is the local precipitation of SiO_2 or $CaCO_3$, as suggested by detailed field studies of exhumed subduction thrusts that document intense calcite and quartz veining within and adjacent to major faults [e.g., *Kimura et al.*, 2012; *Moore et al.*, 2007]. Precipitation would increase the abundance of these minerals, both of which exhibit velocity-weakening behavior [e.g., *Blanpied et al.*, 1995]. Increased shear strain and the accompanying localization of shear with increased depth may also cause a transition to slip-weakening behavior [e.g., *Scruggs and Tullis*, 1998]. Furthermore, embrittlement and slip localization are likely to focus fluid transport, and thus the precipitation of quartz or calcite. We suggest that mineral precipitation and shear localization act in concert to drive the transition in frictional properties. These processes would also lead to heterogeneity in fault frictional behavior due to spatial variations in shear strain, fault architecture, and fluid flow and mineral precipitation. This view is highly consistent with recent conceptual models of a complex and "patchy" seismogenic zone [e.g., *Wang and Bilek*, 2011].

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