The Upper Transition From Seismic To Aseismic Faulting on Subduction Megathrusts

Intellectual Merit of the Proposed Research

Seismogenesis and the updp transition from seismic to aseismic faulting along subduction plate boundaries is one of the most important unsolved problems in fault mechanics. A primary goal of this proposal is to illuminate the processes that control this transition, and therefore whether faults fail catastrophically in large earthquakes or by aseismic creep. Identifying these processes is essential to understanding the seismic cycle and predicting the behavior of subduction zones on time scales relevant to tsunami generation and seismic hazard.

The seismogenic zone of Earth’s crust and upper mantle is defined by the region that hosts earthquakes. In most areas this region does not extend to Earth’s surface. Instead, the shallowest portion of the plate boundary experiences stable, aseismic creep, which can slow seismogenic rupture and facilitate tsunami generation –as occurred in the M9 Sumatra-Andaman 2004 event. The transition from seismic to aseismic faulting is poorly understood because process-based models of the transition on real-world faults are lacking. At present, there is a dearth of the detailed laboratory data needed to understand the important linkages between hydrologic-, elastic-, and frictional properties as related to frictional stability. A central problem in evaluating relevant hypotheses for the updp stability transition is a lack of detailed laboratory data that elucidate the effects of mineral transformation, diagenesis, cementation, and compaction.

A primary motivation for this proposal is the need to link fault zone physical properties with frictional stability. This link is one of the keys to making effective use of direct sampling (via drilling) and detailed marine-based imaging of plate boundary fault zones.

We propose to test hypotheses for the updp limit of the seismogenic zone using a complementary set of laboratory-based approaches. The proposed laboratory experiments will involve: (1) Frictional properties – The effect of lithification and consolidation state, clay mineralogy, effective stress, and drainage conditions on frictional constitutive properties. (2) Fluid transport properties – Laboratory experiments on the relationship between lithification and consolidation state, composition, permeability, and rheology.

We propose to work with an unparalleled suite of samples including field samples of exhumed faults, samples collected by ODP drilling, and synthetic fault gouge. We propose to test hypotheses for the upper stability transition by conducting carefully controlled laboratory experiments on natural and synthetic samples over P-T, fluid, mineralogical, cementation, and compaction conditions that span the stability transition. The proposed experiments offer a unique opportunity to integrate results from a broad range of investigations with the common goal of identifying mechanisms that determine the updp limit of subduction zone seismicity.

Broader Impacts of the Proposed Research and Data Sharing

Significant societal impact will result through improved understanding of fault mechanics and earthquake physics including tsunami generation and seismic hazard assessment. The proposed effort is highly complimentary to other NSF/OCE initiatives including those of the IODP and Margins programs. For example, the proposed research will establish a framework for shorebased investigations of frictional properties of samples derived from coring such as planned for Nankai Trough and other future drilling efforts.

The project will encourage interactions among geoscience communities and provide research and professional opportunities for students. The project will train two graduate students and four undergraduate students. The PI’s will ensure that all students have opportunities to present research at professional meetings, to collaborate with colleagues at other institutions and internationally, and to broaden their understanding of interdisciplinary problems involving fault mechanics, hydrogeology, and earthquake physics.

The PI’s will preserve and share all data and samples deriving from this project, and will rapidly archive and disseminate data and other results.
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Preface: This is a revised version of a proposal submitted to the MG&G panel in February. That proposal reviewed favorably (Panel Score of 1.3, where 1 is excellent and 5 is poor, and mail reviews of E, E, E/VG, VG) but was not funded due to program budget limitations. Reviewers of the previous proposal will find that the current document is very similar to that submitted in February. The motivation for the proposed work and the plan to conduct detailed laboratory experiments using a suite of natural fault zone materials is the same. Based on review comments, we have revised the scope of the proposed sample suite slightly, to put more emphasis on samples and field sites directly relevant to subduction zones.

Broader Impacts of the Proposed Research: The proposed experiments are very important for improving our understanding of earthquakes and faulting in marine settings. This work is a critical step in preparing for the unprecedented core recovery of in-situ fault zone materials in upcoming IODP, Earthscope, and ICDP fault zone drilling. Results of the present study will help maximize the return from these efforts and establish a framework for shore-based investigations of frictional properties of samples derived from drilling. Significant societal impact will result through improved understanding of faulting, including tsunami and seismic hazard assessment. The proposed project will encourage interactions among geoscience communities and provide research and professional opportunities for students. The project will train two graduate students and four undergraduate students. The PI's will ensure that students have opportunities to present research at professional meetings, to collaborate with colleagues at other institutions and internationally, and to broaden their understanding of interdisciplinary problems involving fault mechanics, hydrogeology, and earthquake physics.

1. Introduction and Project Motivation

Subduction zone megathrusts host the world’s largest and most damaging earthquakes (e.g., Ruff, 1996). Determining the location and extent of the seismogenic zone for these systems is a central problem in earthquake and fault mechanics and is of paramount importance in assessing tsunami risk and earthquake hazard. While it is generally agreed that the down-dip limit of seismicity is controlled by the onset of crystal plasticity (e.g., Sibson, 1982; Scholz, 1998), there is little consensus regarding the mechanisms that determine the updip limit of the seismogenic zone (Figure 1; Scholz, 1988, 1989; Bilek et al., 2004; Schwartz and Deshon, 2005).

![Figure 1](image-url)

**Figure 1.** Sketch of a subduction megathrust showing the transition from shallow aseismic slip to seismogenic faulting (based on seismic line in the Nankai Trough from Park et al., 2002). Bold red line depicts hypothetical region of co-seismic slip based on the 1944 Tonankai (M8.1) earthquake. Boxes and arrows illustrate the analogous positions of samples from drilling and field study of exhumed faults that are available for the proposed work. Numbers indicate ODP site number for existing core samples; Kodiak Island and San Gregorio are locales of well-studied exhumed faults. CR = Costa Rica, NT = Nankai Trough, SGF = San Gregorio Fault.
Two main hypotheses for the updip stability transition have been proposed. The clay mineral hypothesis posits that a thermally-driven transition from a hydrous (smectite) to an anhydrous (illite) clay structure produces the transition (Hyndman et al., 1995, 1997; Scholz, 1998). According to this view, smectite clays within the shallow portion of subduction faults promote stable, aseismic behavior, whereas illite-rich fault gouge exhibits potentially unstable behavior. An alternative idea, which we refer to as the lithification hypothesis, posits that cementation and consolidation of the fault zone and surrounding rocks causes a stability transition due to a decrease in $D_c$, the critical friction slip distance, and a switch to velocity weakening frictional behavior. According to this view, aseismic behavior is associated with distributed deformation in the fault region, whereas localized shear within the fault zone leads to the necessary and sufficient conditions for instability (e.g., Marone and Scholz, 1988; Byrne et al., 1988; Moore and Saffer, 2001).

Each of these hypotheses have merit and neither can be ruled out by existing laboratory or field observations. Despite significant recent progress by many investigators, process-based models are lacking for the mechanisms and conditions that determine fault stability in the shallow portion of fault zones. It is important to move beyond descriptions and improve our understanding of the processes that determine the upper boundary of seismogenesis in plate boundary megathrusts.

This proposal is to support a comprehensive laboratory-based investigation that will elucidate the mechanisms that determine the transition from stable, aseismic slip in the shallow portion of subduction zones to frictionally unstable, seismic faulting, and lead to an understanding of how to link rock and sediment physical properties with frictional stability. We will work with an unparalleled suite of samples from ODP driling, field sampling of exhumed faults, and synthetic fault gouge that provide direct analogs for portions of active subduction zones, and which span depth and temperature conditions straddling the transition in slip behavior (Figure 1). Specifically, we propose to conduct laboratory measurements of hydrologic, frictional, and elastic properties under carefully controlled P-T, fluid, mineralogical, cementation, and compaction conditions that span the upper regions of the world’s subduction zones, to test the two hypotheses for the upper stability transition noted above. These new data will be integrated into existing thermal and hydrologic models. Because our proposed work addresses the fundamental and global problem of seismogenesis in subduction zones, our results will be broadly applicable.

2. Research Objectives

- Test hypotheses for the updip transition from aseismic to seismic faulting. Use natural samples from within and around plate boundary décollements to study the effects of their preserved lithification state (mechanical consolidation and chemical cementation), mineralogy, and laboratory-altered lithification state on frictional properties, permeability, and consolidation properties. Perform high-precision strength, friction, and hydrologic studies under carefully controlled boundary conditions at temperatures to 250°C, effective stresses to 250 MPa, and fluid pressures to 70 MPa.
- Merge laboratory results with ongoing modeling studies of progressive clay dehydration and consolidation/dewatering in the PI’s groups (which are supported by other funds) to “map” frictional properties with increasing depth along the subduction plate interface.
- Investigate the relationship between frictional behavior (including healing and velocity dependence), fault zone mineralogy, and lithification state as defined by measurements of cohesion and elastic moduli.
- Develop advanced laboratory techniques for investigation of fault zone core and plate boundary materials. Establish a framework for integrating these data with borehole measurements, and prepare for lab-based investigations of frictional and hydrologic properties of samples derived from limited core.

3. Background

Plate boundaries can generally be divided into three main zones as a function of increasing depth: an aseismic updip zone, the seismogenic zone, and a deep aseismic zone (Figures 1-2). Recent work has illustrated that the updip transition is more complex than expected from a simple thermal
or depth-dependent transition, in that slip behavior near the updip limit of geodetic locking exhibits patches of stably sliding material adjacent to patches that fail by stick-slip (e.g., Bilek et al., 2004; Schwartz and DeShon, 2005). Moreover, subduction zone megathrusts host a wide range of fault behaviors, including interseismic creep, slow earthquakes, earthquakes with normal (fast) rupture velocity, tsunamigenic earthquakes, postseismic slip, and fault healing (Dragert et al., 2001; Miller et al., 2002; McGuire and Segall, 2003; Obara and Ito, 2005; Ito and Obara, 2006).

Many factors influence the properties of fault zone rocks in subduction zones and thus are potentially important in controlling frictional behavior and slip localization. These factors include sediment composition and grain size (e.g., Lupini, 1981; Logan and Rauenzahn, 1987), temperature (Chester, 1994), normal stress (Mair and Marone, 1999), changes in mineralogy caused by initial variations and progressive down-dip changes (e.g. Hyndman et al., 1995, 1997), consolidation state (Zhang et al., 1993; Davis et al., 1994), and cementation and changes in permeability (Ko et al., 1997; Tenthorey et al., 1998; Zhang and Cox, 2000; Bos et al., 2000; Bos and Spiers, 2002; Streit and Cox, 2001, 2002; Tenthorey and Cox, 2003). However, despite their probable importance in controlling the frictional and hydrologic properties of fault zone rocks, the influence of these factors on fault stability is poorly understood. We propose to test two widely held geologically-based hypotheses for the upper stability transition, each of which incorporates and links several of the processes listed above.

3.1 Hypotheses for the Upper Stability Transition

In the context of rate and state friction, a fault zone that exhibits velocity-strengthening frictional behavior will undergo aseismic deformation. This implies that the seismogenic zone, as defined by earthquake nucleation, maps the transition from stable, velocity strengthening frictional behavior to unstable, velocity weakening behavior (Figure 2). At any given depth, earthquake nucleation is dictated by the local friction rate parameter \( (a-b) \), effective normal stress, and the critical stiffness \( K_c \), where \( K_c = (\sigma_n)(a - b)/D_c \) (Scholz, 1990). The experiments we propose will comprehensively evaluate each of these parameters for P-T-fluid conditions spanning the stability transition.

It has been widely held that the updip limit of seismogenesis in subduction zones is tied to the thermally-driven transformation of smectite to illite. This hypothesis stems from (1) studies indicating that the transformation is complete by temperatures of 120-150° C (e.g. Pytte and Reynolds, 1988), (2) laboratory studies that demonstrate a difference in frictional strength between smectite and illite, and (3) correlation between the location of the 150° C isotherm predicted by thermal models, and the observed seismic front along subduction zones (Hyndman et al., 1997; Oleskevich et al., 1999). This hypothesis explicitly assumes that smectite exhibits velocity strengthening frictional behavior and that illite exhibits velocity weakening frictional behavior.

A second hypothesis is that the upper stability transition reflects a threshold lithification state within fault zones resulting from cementation and mechanically-driven consolidation (Marone and Scholz, 1988; Davis et al., 1994; Moore and Saffer, 2001; Saffer and Marone, 2003; Moore et al., 2005). In this view, poorly consolidated fault rocks – and the surrounding material – undergo distributed deformation. Existing work shows that shear via distributed and pervasive deformation results in velocity strengthening frictional behavior (e.g., Marone et al., 1992) and inherently stable shear (Figure 2). According to the lithification hypothesis, at a critical depth –which depends on temperature, effective stress, fault slip rate, and mineralogy– deformation localizes, and the necessary and sufficient conditions for instability, \( K < K_c \), are met. This hypothesis is supported by laboratory experiments showing that unstable, stick-slip behavior is linked to slip localization and velocity-weakening frictional behavior, whereas stably-sliding behavior is linked to distributed shear and velocity-strengthening (e.g., Dieterich, 1979, 1981; Ruina, 1983; Chester and Logan, 1986; Marone et al., 1992; Sleep, 1995, 1997; Beeler et al., 1996; Tullis, 1996; Marone, 1998). The lithification hypothesis is also consistent with the conceptual model of Davis (1994), in which decreasing sediment porosity with increased burial in subduction zones is tied to a transition from ductile to brittle behavior, based upon the observation of localized shear in a small number of triaxial experiments.
We will test the clay transformation hypothesis by conducting laboratory experiments on (a) a suite of natural samples that have undergone the transformation to varying stages of completion, and (b) synthetic gouges that represent end-member compositions. As described in detail below, these experiments will be carried out over a wider range of experimental conditions than previous work, to comprehensively evaluate the hypothesis. By using samples that have undergone the transformation in nature, the effects of any accompanying changes to fabric, grain contacts, and cementation can be evaluated. We will test the lithification hypothesis by characterizing and quantifying relationships between frictional behavior and poro-elastic properties, and (a) elastic moduli, (b) porosity, and (c) cementation as metrics for lithification state. Experiments will be conducted for a suite of samples and over a wide range of experimental conditions. If changes in friction parameters correlate with increased lithification, the experimental results would not refute the hypothesis.

Each of these hypotheses have merit and neither of them can be ruled out by existing laboratory data or field observations. Our previous work on clay-rich synthetic fault gouge (Saffer et al., 2001; Saffer and Marone, 2003) casts doubt on the clay mineral hypothesis because illite-rich gouge exhibits only inherently-stable, velocity strengthening frictional behavior. However, those experiments have investigated a limited range of P-T and fluid conditions. The clay mineral transformation hypothesis must be tested with higher temperature experiments, with experiments that include partial and in-situ smectite-illite transformation, and under controlled fluid pressure (and clay hydration state). Likewise, the lithification hypothesis must be tested under a broad range of conditions.

![Conceptual diagram of the seismogenic zone and updip transition from seismic to aseismic faulting, as illustrated by an example of seismicity vs. depth from the San Andreas fault in Parkfield, CA. The upper stability transition is shown by grey shading. Note the transition in porosity and modeled fluid pressure ratio $\lambda^*$ (from Saffer, 2002), which coincides with temp. of 125-150 °C and a range of diagenetic processes (after Moore and Saffer, 2001; Saffer and Marone, 2003).](image)

4. Preliminary Results and Proposed Work

We propose a coordinated suite of laboratory studies on natural samples collected from plate boundary fault zones and from a range of P-T conditions that span the aseismic-seismic transition (Figures 1 & 2). Friction studies will define $(a - b)$ and $D_e$, while consolidation tests, measurements of elastic properties, and permeability will constrain elastic stiffness $(K)$ and effective stress $(\sigma_e^*)$.

4.1 General Work Plan

We will conduct coordinated experiments on intact and granulated natural samples chosen to span P-T conditions from aseismic slip at <2-3 km depth to seismogenic slip at >5-10 km depth (Figure 2). Experiments will be conducted under effective stresses ranging from 1-250 MPa, under controlled pore pressure, and with shear strain rates from $10^{-5}$ to $10^{-2}$ s$^{-1}$. Temperature will...
range from 20 to 250° C and fluid pressures will range from 0.1 to 70 MPa. **We will study a range of materials, including intact samples of fault rock that preserve cementation, mineralogy and other features related to their in situ state. The temperature- and depth-driven changes relevant to the upper stability transition already exist in the samples. Thus, these samples will provide constraints on the effects of diagenesis or prograde metamorphism on frictional and hydrologic behavior. In all cases, sample thermal and structural history and geologic and petrologic characteristics are well documented by previous and allied work (see detailed description of samples below).**

We anticipate performing experimental measurements on approximately 40 individual sample sets, or ~10 or more sets for each setting laid out below. The range of experimental observations will vary with sample type (e.g., fault gouge vs. host rock, un lithified vs. lithified), but will include:

- **Frictional constitutive properties** through biaxial direct shear experiments on intact sample “wafer” and powdered gouge and fault rock.
- **Permeability and consolidation properties** as functions of porosity, lithology, and lithification state, measured by uniaxial deformation and flow-through tests. Permeability experiments will be conducted on intact samples of fault and wall rock in a dedicated apparatus, and also during frictional shear in the biaxial vessel.
- **Lithification state and mineralogy** of the natural samples will be assessed by: (1) measurement of stress-strain relations and defining the relevant moduli from these data, (2) XRD to document composition, (3) thin section and SEM analysis to characterize extent and composition of cements, grain size distribution, and fabric, and (4) porosity measurement. Many of these data (e.g., mineralogy and fabric observations) have already been obtained in extensive ongoing geological studies by others (e.g., Steurer and Underwood, 2003, Ikesawa et al., 2003; Moore et al., 2005).

The experimental effort will be collaborative between the P.I.’s; this is straightforward in that Marone and Saffer share laboratory space and currently co-advice graduate student research. Project year one will focus on measurements of frictional behavior, permeability, and elastic parameters. Project years two and three will focus on (1) completion of the suite of measurements, (2) integrated measurements of frictional shearing, permeability, and elastic properties, and (3) integration of the data into existing thermal and hydrologic models. Sample characterization, consultation with colleagues working on the geologic framework for the samples, data reduction and analysis, associated modeling, and publication of results will be conducted throughout the project.

### 4.2 Laboratory Friction Studies

We have conducted preliminary experiments for this proposal on materials representative of plate boundary fault zones (Figures 3 and 4). The experiments included shear of thin wafers cut from intact material as well as layers of powdered rock and fault gouge. Materials included core from ODP leg 190 drilling in the Nankai subduction zone, core from phase 1 EarthScope/SAFOD drilling, rocks from the Ghost Rocks Formation, Kodiak Islands Alaska, fault gouge material from the San Gregorio fault, and synthetic fault gouge composed of mixtures of clay and quartz.

Two samples from Nankai were selected specifically as illite-rich and smectite-rich endmembers, and are composed of ~55% clay, ~32% quartz, and ~10% plagioclase. Of the clay fraction, the illite-rich sample (190-1174, from 843.3 mbsf) is composed of 18% smectite, 52% illite, and 30% chlorite; the smectite-rich sample (190-1177, 792.2 mbsf) is composed of 67% smectite, 22% illite, and 11% chlorite. The SAFOD samples were wall rock of granodiorites and arkosic metasedsandstones from depths of 1462.4 m (sample B1), 3062.9 m (B18), and 3065.5 m (B21). The Ghost Rocks samples consist of metamorphosed hemipelagic shale and turbidite intermixed with pseudotachylyte and breccia. For shear of powdered layers, rock chips were crushed to < 500 μm and friction experiments were conducted on 3 to 5-mm thick layers of the powdered samples in the double direct shear configuration (Figure 3a inset). Investigation of powdered samples provides information on the behavior of fault gouge derived from the host rock. In the proposed work, we will also shear intact wafers obtained from drilling and outcrop sampling, so that the original fabric from consolidation and/or shearing is not destroyed. Preliminary experiments of this type were conducted
on 4-mm thick wafers of intact sample sheared along the dominant fabric (Figure 3a). We compared the behavior of the natural materials to an illite shale and end-member, synthetic fault gouges. The illite shale is similar to clay- and mica-rich gouges used in previous experimental work, and to natural fault gouges, including that form from marine sediments in subduction zones (e.g., Reinen et al., 1991; Vrolijk and van der Pluijm, 1999; Wang et al., 1978; Wang and Mao, 1979; van der Pluijm et al., 2001; Solum et al., 2004). Synthetic gouges were mixtures of Ca-montmorillonite, Na-montmorillonite, illite-shale, and granular quartz (Saffer and Marone, 2003; Ikari et al., 2005; Marone et al., 2005).

Experiments were carried out in the double-direct shear configuration (Figure 3a) in which layers are sheared under constant normal stress, ranging from 5 to 150 MPa, sliding velocities of 0.1 μm/s to a few mm/s, and under controlled humidity at room temperature. Normal stress on the layers is maintained by a fast, hydraulic servocontroller, and changes in porosity are monitored continuously as a function of slip and time. Stress-strain curves for the preliminary experiments show that steady state frictional sliding is reached for both intact material and powdered fault rocks (Figure 3).

We propose to employ a normal stress stepping procedure to efficiently evaluate the Coulomb failure envelope and friction constitutive properties at a range of fault depths with limited sample material (Figure 3). Experiments begin with a ‘run-in,’ to a shear strain of 1-4, which promotes consolidation (e.g., Zhu et al., 1997) and establishes a steady-state fabric and friction level (e.g., Marone, 1998). After changing normal stress, we imposed a further run-in prior to detailed measurements of frictional properties.

Data from the preliminary experiments exhibit linear Coulomb failure envelopes for the range of normal stresses studied (Figure 4). The SAFOD samples show consistent values of the coefficient of sliding friction (we assume zero cohesion for the granulated layers) ranging from 0.57 to 0.63 (Figure 4). The Ghost Rocks Formation samples show friction values in the range 0.34 to 0.44 (Figure 4), which is consistent with the high clay contents in those samples. Frictional strength varies systematically with quartz content in smectite-quartz mixtures (Figure 3d). The experiments shown in Figure 3 include sections of constant loading velocity as well as perturbations in the loading rate, which appear as transients in the normalized shear strength.

Figure 4 shows data from experiments that examined the effect of hydration state on the frictional properties of mixtures of Ca-montmorillonite and quartz powder. Four mixtures were
studied (100%, 70%, 50%, and 30% montmorillonite) and each was tested at a range of hydration states and normal stresses. Samples with water content values approaching 0 wt% were dried in a 105 °C oven for at least 24 hours. Time dependent drying curves were constructed in order to reproducibly obtain a given hydration state. Samples reached 14 wt% water when equilibrated with room RH. Higher water content was achieved by equilibrating samples in a sealed environment with saline solutions for at least 24 hours. Layers were 3 to 5 mm thick with nominal contact dimensions of 5 cm by 5 cm. For each clay/quartz mixture and hydration state, we measured frictional properties at normal stresses of 5, 15, 25, 40, 70, and 100 MPa. Velocity stepping experiments were conducted in the range 1-300 μm/s. Preliminary results show a systematic decrease in frictional strength with increasing water content and with increasing normal stress and increasing clay content.

In the proposed work, we will also perform velocity stepping tests at each normal stress to evaluate the slip rate and history (state) dependence of friction (e.g., Figure 5). Preliminary results show that our procedures are successful in attaining steady-state friction values, and that Nankai, Ghost Rocks, and SAFOD samples exhibit typical rate-state dependent friction behavior. That is, a sudden increase in load point velocity results in an immediate increase in friction followed by a displacement decay to a new steady-state level (Figure 5). The friction parameter (a-b) is a measure of the change in steady-state friction with velocity (see Figure 5b). We will model friction data using the full rate and state friction law with elastic coupling between the testing apparatus and shearing layers (e.g. Marone, 1998).

Notably, in our experiments illite shale exhibits only velocity-strengthening frictional behavior (i.e. the steady-state coefficient of sliding friction increases with increasing sliding velocity) over a wide range of normal stresses (5-150 MPa) and sliding velocities (0.1 – 200 μm/s) (Figure 5). Layers of pure smectite exhibit a transition from velocity weakening at low normal stress to velocity strengthening at higher normal stress (Figure 5c). These behaviors are mimicked by the Nankai samples, with the illite-rich sample showing only positive (a-b) and the smectite-rich sample showing velocity weakening at lower normal stresses. Our previous work shows that these results are independent of net displacement as long as shear strain values are > 4-5 and the layers have been subject to the ‘run-in’ described above (Saffer and Marone, 2003). Post-experiment examination of the Ghost Rocks wafers shows that the samples remain intact and that shear is accommodated by a combination of pervasive strain and localized shear.

Contrary to the hypothesized velocity-weakening frictional behavior of illite clay invoked to explain the onset of seismogenic slip at subduction zones, illite shale exhibits only velocity strengthening behavior for the range of conditions explored under carefully controlled boundary conditions. These data are inconsistent with the clay mineral hypothesis for the updip limit of the seismogenic zone. However, with existing data, we cannot rule out the possibility of velocity-weakening behavior at higher temperatures, larger shear strains, or under a wider range of saturation states. Additional experiments are necessary to understand the role of fluid pressure, temperature, and other factors in bringing about the transition from stable to unstable frictional behavior.
Figure 5. (a) Velocity stepping tests on powdered illite shale showing friction behavior and definition of rate/state friction parameters. (b) Friction behavior for an intact sample of Ghost Rocks Formation showing velocity strengthening. (c) Friction rate parameter (a-b) for the Nankai samples, illite-shale, and smectite clay sheared under nominally dry conditions. Layers of pure smectite and the smectite-rich Nankai sample show a transition from velocity weakening frictional behavior at low normal stress to velocity strengthening behavior at higher normal stresses. Illite shale and the illite-rich Nankai sample exhibit only velocity-strengthening behavior over the range of conditions studied. After Saffer and Marone (2003)

Need for Experiments to Explore the Role of Temperature, Fluid Pressure, and Lithification State:

The proposed experiments will be conducted under controlled temperature and pore fluid pressure using a newly constructed pressure vessel (see Facilities sections for details). This vessel allows true triaxial deformation with independent servo-control of pore pressure and confining pressure. A wide range of pore-fluid flow paths are possible in the double direct shear geometry; each of the forcing blocks has internal fluid conduits. The proposed experiments will include both constant pore pressure and constant flow rate boundary conditions. Porous frits will ensure ample fluid access to the shear zone during deformation.

We conducted preliminary experiments with quartz gouge to assess the role of temperature and fluid saturation at 65°C. These tests were done prior to completion of the pressure vessel, so the entire double direct shear sample assembly was placed inside a temperature controlled fluid containment chamber, which was filled with deionized water (Yasuahara et al., 2005). These tests measured frictional healing $\Delta \mu$ in slide-hold-slide tests. At 65°C there is a distinct transition of $\Delta \mu$ data between 1000 and 3000 s. The preliminary data show a six-fold increase in the rate of healing, from 0.0041 to 0.026 per decade. One explanation is that fluid-assisted processes such as pressure solution transfer are activated and influence friction. Similar frictional healing mediated by pressure solution processes has been documented by microstructural analyses (Hickman and Evans, 1991, 1992, 1995; Olsen et al., 1998; Kanagawa et al., 2000; Bos et al., 2000; Bos and Spiers, 2002; Tenthorey et al., 2003; Muhuri et al., 2003).

The temperature used is significantly lower than those of most previous lab and modeling studies focused on pressure solution (Dewars and Ortoleva, 1990; Hickman and Evans, 1991, 1992, 1995; Chester and Higgs, 1992; Fredrich and Evans, 1992; Karner et al., 1997; Zhu and Wong, 1997, 1999; Blanpied et al., 1998; Hajash et al., 1998. Kanagawa et al., 2000; Muhuri et al., 2003; Faulkner and Rutter, 2003; Colon et al., 2004). One reason for that was to establish a lower limit to the resolution of our technique. Previous works have had difficulty resolving effects of relatively modest temperature changes on friction and transport properties. However, our preliminary data show that measurable changes can be resolved even at temperatures as low as 65°C. We propose to extend these experiments to 250°C, and investigate the role of consolidation state, clay mineralogy, effective stress, and drainage conditions on friction behavior and healing.
4.3 Laboratory Permeability and Consolidation Studies

Recent studies have highlighted key relationships between permeability, fluid production, and fault slip behavior (e.g., Rice, 1992; David et al., 1994; Kato et al., 2004; Faulkner and Rutter, 2003; Schwartz and DeShon, 2005). However, these relationships remain somewhat unconstrained, mainly because few data exist to directly relate fault and wall rock hydrologic properties to frictional and elastic properties, or permeability to depth, temperature, or mineralogy in subduction zones (Caine et al., 1996; Faulkner and Rutter, 2003). Fault zone and wall rock permeability architecture are intimately linked to the hypotheses for unstable slip described above, in that (1) permeability is one primary control on the development and localization of elevated fluid pressure, which impacts sliding stability via its influence on effective stress (e.g., Scholz, 1998; Moore and Saffer, 2001); (2) permeability controls the rate of dewatering and sediment consolidation, which is directly related to lithification state and rheology (e.g., Davis et al., 1994; David et al., 1994); and (3) fluid flow pathways and rates are a limiting factor in many diagenetic processes that lead to lithification (i.e. cementation and precipitation) (e.g., Moore et al., 2005). In addition, fault rock (gouge) permeability mediates dynamic fluid pressurization during rapid slip that could lead to slip-weakening (e.g., Sleep and Blanpied, 1992; Ko et al., 1997; Andrews, 2003; Rice, 2006).

Permeability data are also used to parameterize numerical models of fluid flow at depths that span the aseismic-seismic transition. Laboratory data that define systematic relationships between permeability, porosity, and temperature (Figs 6-7) (Kato et al., 2004) are critical, because many such models extend to 10-15 km depth, considerably deeper than drilling can sample. Consolidation experiments, which will be conducted concurrently with permeability measurements, provide key constraints on sediment stiffness (related to bulk modulus) over a wide range of porosities/stresses, and at longer time-scales than sampled by ultrasonic measurements. These data are important as a proxy for the lithification state of experimental samples, and toward assessing the wall and fault rock stiffness in the context of the sliding stability criterion (see discussion in Sections 4.1 & 5.4).

Figure 6: (A) Stress-strain behavior from uniaxial consolidation experiments on a carbonate ooze sample from the Costa Rican trench (blue), and two hemipelagic mudstone samples from the Nankai Trough (red and green) at effective stresses up to 48 MPa. (B) Stiffness measured from stress-strain behavior as a function of sample porosity for the same samples (same color scheme). Note the non-linear increase in sample stiffness at porosities <25-27% for the mudstones, and a similar transition at ~45% porosity for the carbonate ooze.

Previous work suggests that scale-dependence of permeability is important for crystalline rock (i.e. permeability increases with measurement scale as more transmissive zones are encountered) (e.g., Brace, 1980). In contrast, for argillaceous rock and sediment, minimal scale dependence is indicated by agreement between regional scale permeability constrained by inverse modeling and core-scale measurements (e.g., Neuzil, 1994). Recent work on fine-grained sediments from subduction zones further demonstrates that core-scale (matrix) permeability is the key factor in controlling dewatering, consolidation, and thus lithification (Saffer and McKiernan, 2005; Screaton and Saffer, 2005; Gamage and Screaton, 2003). Consolidation and permeability experiments have been conducted on several samples from the Costa Rican and Nankai subduction zones. These
samples include clay-rich hemipelagic sediments typical of those accreted and underthrust at subduction trenches, and within which subduction megathrusts and associated splay faults form. In addition, we have conducted tests on several samples of carbonate-rich ooze from Costa Rica. The results of deformation experiments, conducted at effective stresses up to 25-48 MPa, provide information about stress-strain behavior and therefore compressibility (or stiffness) (Figure 6), and permeability (Figure 7) as functions of effective stress and porosity.

These experiments were conducted using a mechanically driven oedometer with a 50 kN load frame, on cylindrical samples of 38 and 50 mm diameter. Samples were cut from drill core, and trimmed using a series of precisely machined guides to the desired diameter and to a height of 20 mm (for 50 mm diameter) or 13.5 mm (for 38 mm diameter). Samples were then placed in a steel fixed ring that maintains a condition of zero lateral strain, and backpressured for 24 hr to ensure saturation and that any gases present were in solution. Deformation tests were conducted either in a constant rate of strain mode (CRS tests), or stepped loading. In CRS tests, axial displacement was imposed at a constant rate ranging from $10^{-2}$ to 1 $\mu$m/min, and the resulting stress and sample pore pressure recorded. In stepped loading tests, axial stress was incremented every 24 hr, and sample height and pore pressure monitored. Permeability measurements were conducted at several stages in stepped loading experiments by flow through tests at several different flow rates, maintained using a high-precision flow pump connected to a port at the sample top (e.g., Saffer et al., 2000; Saffer and Mckierman, 2005). Equilibrium pressures were confirmed by comparing fluid outflux at the sample base to the controlled flow rate in to the sample top. Permeability was also calculated as a continuous function of deformation during CRS tests, using the measured change in load, change in sample height, and basal pore pressure (following Wisn et al., 1971). Comparison of preliminary results for the CRS and flow-through methods indicates excellent agreement (Saffer and Mckiernan, 2005) (Figure 7).

Preliminary work has been highly successful toward all of the work proposed here (Saffer and Mckierman, 2005; Mckierman and Saffer, 2005) (Figs. 6-7). The results of our preliminary work indicate significant non-linear strain hardening during consolidation, which is typical of clay-rich soils and sediments, but is generally only measured at low stresses (<1-3 MPa) and high porosities (e.g., Mitchell, 1976; Olson, 1985). For the hemipelagic mudstones from Nankai, for example, preliminary results indicate that stiffness increases sharply below ~25% porosity, from values of ~50 MPa to >100 MPa (Figure 6). This provides a key indication that significant and resolvable changes

**Figure 7.** A. Permeability as a function of porosity, for mudstone samples from the Lower Shikoku Basin facies at drill sites 1177 and 1173 offshore Nankai. Data from samples 1177-19R (squares) and 1173-49X (circles) are shown. Estimated in situ temperature is ~85-90° C for 1173-49X whereas it is only ~50° C for 1177-19R. The higher in situ temperature, accompanied by silica cementation at 1173 (Moore et al., 2001) may explain the lower permeability of 1173-49X. B. Permeability as a function of porosity, for mudstone samples from drill sites 1039, 1040, 1254, and 1255 offshore Costa Rica. Data from samples 1254-16R (small circles), 1255-2R (squares), 1255-3R (diamonds), and 1255-4R (triangles). Data for comparable samples from Sites 1039 and 1040 (Saffer et al., 2000) are also shown (large circles at porosities >60%). For both panels, porosity range corresponds to effective stresses from 0.2 to 47 MPa. Open symbols show data from CRS tests; filled symbols show data from flow-through tests. For clarity, only every fifth data point from CRS tests is plotted. Note (1) the excellent agreement between the two methods for each individual sample, and (2) the similar relationship between log (k) and porosity, for multiple samples and over a wide range of porosities.
in sample moduli occur with increased consolidation, which is one key element of the lithification hypothesis.

Our data from both margins also indicate a well-characterized log-linear decrease in permeability with decreasing porosity (and with increasing effective stress) (Figure 7). In addition, preliminary data from Nankai show the potentially important effects of in situ temperature on permeability. Two samples of comparable composition, clay content, and burial depth were sampled at two drill sites separated by ~100 km along-strike (sample 1173-49X at 464 m depth; sample 1177-19R 482 m). Site 1173 falls along a transect in which heat flow is ~180 mW m⁻², higher than the regional average of 100-120 mW m⁻² (Moore et al., 2001); accordingly, the estimated in situ temperature is 85-90°C for sample 1173-49X, and only ~50°C for sample 1177-19R. Permeability is 4-5 times lower for the sample with higher in situ temperature (Figure 7A); we hypothesize that this is a result of silica cementation related to either illitization or opal diagenesis (e.g., Moore et al., 2001). The proposed work will provide key data to relate in situ temperature to permeability. Notably, the intact samples preserve cementation, mineralogical, pressure solution, and compaction features related to their in situ thermal state. Thus, permeability measurement at elevated temperature in the laboratory is not necessary (although it is possible) because any temperature-driven changes relevant to occlusion of pores already exist in the samples – and therefore do not need to be generated in the lab.

6. Detailed Work Plan

Objectives: We propose to conduct an integrated suite of experiments on a set of samples that comprehensively represent subduction-related faults and their host rock at P-T conditions spanning the transition from seismogenic to aseismic (Figures 1 & 2). We will work with an unparalleled range of samples from prior ODP drilling, other borehole analogs, and field sampling of exhumed faults. Experiments will be conducted on intact samples that preserve fabric, mineralogy, and cementation occurring at depths ranging from <1 to >12 km, and at temperatures from ~30°C to ~250°C. Taken together these samples span a range of lithologies, deformational features, and diagenetic histories covering the likely transition from porous, permeable, low-strength materials of the shallowest faults, to well-lithified fault rocks which exhibit clear evidence of seismogenic behavior.

These proposed experiments will examine the conditions for stable versus unstable frictional sliding in fluid saturated fault zone materials. They will reveal the evolution of mechanical and fluid transport properties under effective stresses to 250 MPa, temperatures to 250°C, and a range of permeants (H₂O, brine) (Table 1). These experiments will be unusually well-constrained to both support the development of self-consistent micro-mechanical models of observed behavior, and to enable the scaling of these component behaviors to field scale.

6.1 Pool of Samples

ODP whole round samples: We have access to intact whole round samples from ODP legs 170, 190, and 205, all of which targeted active decollements or accretionary prism thrust faults. These samples include material from fault zones and wall rock, and represent a range of deep-sea lithologies, thermal regimes, and structural fabrics representative of Nankai, Costa Rica, and other well-studied subduction zones. The samples are the remainder from previous post-cruise studies that focused on physical properties; however, little experimental data on frictional properties exist for this material (but see Brown et al. 2003, Bolton et al., 1999, and other studies). For these samples, the proposed work will focus on direct shear friction experiments, including measurement of permeability and consolidation. The samples have been carefully preserved since their initial collection, and kept sealed in wax and fully saturated with their original pore fluids at 4°C.

Kodiak Accretionary Complex samples: Well-exposed shear zones in the Eocene Sitkalidak and Paleogene Ghost Rocks Formations of the Kodiak accretionary complex occur in rocks metamorphosed to prehnite-pumpellyite facies, exposed to temperatures from 100–125°C (Sitkalidak Fm; 2.4-3.9 km depth) to ~250°C (Ghost Rocks Fm; 10–12 km depth) (Moore and Allwardt, 1980; Vrolijk et al., 1988). Samples from several localities were collected by A. McKiernan during summer 2004, in collaboration with J.C. Moore at U.C. Santa Cruz. The P-T history of these fault zones is well characterized and the samples provide analogous fault zone rocks to those sampled by ODP drilling, but exposed to higher temperatures and pressures and having undergone higher-grade metamorphism. The two sample localities in Alaska have been explicitly
selected to span the shallow, aseismic (Sitkalidak Fm) to deeper, seismogenic (Ghost Rocks Fm) portions of subduction zones. Ongoing microstructural, mineralogical, fluid inclusion, and detailed structural mapping of these shear zones by Moore’s group will provide a comprehensive geologic and petrologic context for the proposed laboratory experiments.

**San Gregorio Fault samples:** Samples for preliminary work have been collected from an exceptionally well exposed, active strand of the San Gregorio Fault zone in central CA, that offsets mud-rich sedimentary rocks (Lohr et al., 1999; Mazzi and Moore, 2000). The fault zone consists of a ∼100 m wide damage zone surrounding a ∼40 m thick gouge-filled core (Lohr et al., 1999). Cumulative offset on this fault is thought to be tens of km (e.g., Stanley and Lillie, 2000). Based on porosity of the sedimentary wall rocks, the fault zone is thought to be exhumed from 2-3 km depth (Lohr et al., 1999). This site, like the Kodiak example, has been the site of detailed microstructural, mineralogical, and geochemical studies (e.g., Yamagata et al., 1996; Mazzi and Moore, 2000).

### 6.2 Double Direct Shear Friction Tests, Flow-Through, and Consolidation

Shear deformation experiments will be carried out using a biaxial loading frame and the double-direct shear geometry. Many of the experiments will make use of a recently constructed pressure vessel that allows true triaxial and hydrothermal deformation experiments at elevated temperature using the double-direct shear geometry (see Facilities section for details). This shear geometry has the capability to accommodate large slip with high-precision force and displacement measurements on relatively large samples. The relative ease of sample construction and preparation allows easy alteration of surface roughness, nominal contact dimensions, and material properties. The lab is in continuous operation and we do not anticipate any delays in conducting a full suite of experiments for this project. Since September 2001 we have run 800+ experiments.

Tests conducted for this project will examine the evolution of permeability, frictional strength, and stiffness of samples. **In particular we seek to define the necessary and sufficient conditions for fluid saturated shear zones to exhibit aseismic creep versus unstable, potentially seismogenic behavior.** The experiments will document the role of sample lithification and hydraulic transmissivity by evaluating the competing critical effects of shear strain, consolidation, dilation, and fluid pressure. Applied shear stresses, normal stresses, and shear rates, will be closely controlled (Table 1).

The double direct shear apparatus comprises a biaxial load frame capable of shearing gouge materials and/or planar fracture sample areas at controlled rate and under prescribed normal and shear loads. The sample comprises a block with the shear surface comprising either one face or two opposing faces of the rectangular prism. In the current configuration, the system can attain displacements of ∼25-35 mm, corresponding to shear strains of 8-20 for typical layer thicknesses used in our experiments. For tests without excess fluid pressures, the block is placed within the biaxial apparatus, and shearing of the two surfaces occurs simultaneously. Lubricated spacers are used to minimize friction and accommodate dilation and compaction normal to the sliding surfaces. Where samples are of limited availability, the tests may be completed with a single shear zone, with the opposing block side replaced by a lubricated bearing and spacers (see Figure in Facilities section). Displacements normal and parallel to the sliding direction are readily measurable with DCDTs and internal load cells will be used for precise measurement of applied shear and normal force.

**Experimental Procedure:** Testing in the double direct shear pressure vessel will be completed with the following typical procedure:

- **Intact samples:** prepare sample by surface grinding square and parallel; friction contact 5 cm x 5 cm or 3.5 cm x 3.5 cm.
- **Install sample within grooved surfaces on porous frits, which secure intact and powdered materials for shearing.**
- **Retain pre-test sample for comparison with post-test analysis (SEM, thin section, water content).**
- **Jacket sample assembly, mount sample in cell, and apply normal stress.**
- **Pressurize cell, raise temperature and equilibrate, and initiate flow-through.**
- **Set normal stress, set shear rate, and shear sample. Monitor shear stress and sample influent and effluent pressures.**
- **Increment/decrement sample or influent temperatures, and flow rates, and flowing components, as desired.**
• Increment sample pressures, or decrement confining-pressure to shear, and continue measurement of permeability via flow through.
• Remove sample at test completion, and scan using SEM. Split some final samples for surface analysis, and resin-impregnates others for thin-sectioning.

6.3 Uniaxial Consolidation, Permeability, Porosity, and Flow-Through

Consolidation will be characterized under uniaxial conditions, which are most appropriate for underthrusting sediments that are transported to depths of seismogenesis, and within which subduction megathrusts typically develop (e.g., von Huene and Lee, 1982; Saffer, 2003). Tests will be conducted using a mechanically driven oedometer in Saffer’s lab (see Facilities pages). Given the small possible sample size (range 25 to 50 mm diameter), we can simulate conditions where the maximum stress is vertical or horizontal, simply by sub-coring samples across or along the in situ vertical axis. Consolidation loads will be applied in two modes: constant rate of strain (CRS), and stepped loading. In CRS tests, axial displacement is imposed, and the resulting stress and sample pore pressure are recorded (Crawford, 1986). In stepped loading tests, the axial load is incremented, typically every 24 hours (e.g., Olson, 1986). Deformation tests will be conducted over a range of effective stresses from 0.1-100 MPa, and at a range of rates (or durations for stepped tests) to quantify time-dependent effects. The stiffness of samples as a function of stress, porosity, composition, and maximum P-T conditions experienced (i.e., as shown in Figure 2), will be documented (Figure 6) to define the relationship between stiffness, consolidation state, and frictional behavior measured in the biaxial apparatus. These measurements will provide key data for evaluation of the lithification hypothesis.

Permeability measurements will also be conducted in the consolidation apparatus for the full suite of samples at several increments of effective stress ranging from 0.1–100 MPa. For fault rocks, permeability will also be measured during shearing in the biaxial system using flow-through techniques (described below), over a range of stress, temperature, and displacement. A small number of additional permeability tests will be carried out on jacketed samples under triaxial conditions up to confining pressures of 14 MPa using a conventional triaxial system in Saffer’s lab, and can be extended up to confining pressures of ~70 MPa and temperatures up to 250° C in the newly constructed vessel in Marone’s lab. Subsampling of both core and outcrop samples will allow measurement in multiple orientations for assessment of permeability anisotropy related to bedding or fabric. Samples will be trimmed to 25, 38, or 50 mm diameter and ~12-20 mm height (with sample diameter ≥2.5 times sample height) using machined blocks to maintain constant diameter and smooth top and bottom faces, and backpressured to 500 kPa for 24 hr to equilibrate.

The consolidation system, which is optimized for sediments, has also been adapted for harder rock samples. These modifications include gasketing at sample top and base, and will eventually include recesses machined into the confining ring for additional hydraulic seals (see Facilities section). To date, the apparatus has yielded high-quality preliminary data on extremely stiff low-porosity (<2-3%) metasediments from the SAFOD borehole using gasketing alone. For flow-through permeability measurements, samples will be deformed in stepped-loading tests (e.g., Olson, 1986). After each consolidation stage, the ram will be locked, and flow through tests conducted at several different flow rates, maintained using a high-precision flow pump connected to a port at the sample top. The pressure difference across the sample will be measured for each flow rate, and permeability determined by solving for a best fit linear relationship between flow rate and pressure difference (e.g., Saffer et al., 2000; Saffer and McKiernan, 2005). This technique minimizes error by obtaining a single permeability datum from several flow rates. Equilibrium pressures are confirmed by monitoring fluid outflux at the sample base to +/- 1 µl; at equilibrium, this flow rate equals the controlled flow rate in to the sample top. Total system volume is also monitored, and temperature is recorded throughout experiments to assess the possibility of any fluid leaks and to quantify effects of temperature changes in the lab. In the consolidation system, permeability can also be calculated as a continuous function of deformation during CRS tests, using the measured change in load, change in sample height, and basal pore pressure (following Wissa et al., 1971).

The flow-through system is optimized for permeabilities ranging from 10^{-20} to 10^{-15} m^2 (Figure 6), but measurements on higher permeability samples is straightforward simply by plumbing in a larger capacity pump capable of higher flow rates. This pump and several high-pressure syringes are currently available in Saffer’s lab. For extremely low permeability samples (<~3 x 10^{-21} m^2), the lab

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Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting  p. C-13
is equipped to measure permeability using transient techniques, such as pore pressure oscillation or pulsing. For measurements in the biaxial system, the same techniques will be used. Pore pressure controllers will be plumbed to ports in the side and center forcing blocks, which will allow permeability measurement both across and along the shearing layer.

The work will provide critical data on (1) permeability architecture of subduction fault systems as a function of porosity, stress, and shearing, and (2) compaction behavior, and will constitute a major component of two PhD theses.

6.4 Experiment Variables and Procedures

<table>
<thead>
<tr>
<th>Process/Factor</th>
<th>Experimental Variable</th>
<th>Experimental Range</th>
<th>Measured Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Effective Normal stress Shear Stress</td>
<td>0.5 to 250 MPa</td>
<td>Frictional properties</td>
</tr>
<tr>
<td></td>
<td>Shear rate or Strain rate Confining Pressure</td>
<td>0.1 to 200 MPa</td>
<td>Stability. Constitutive parameters.</td>
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<tr>
<td></td>
<td>True triaxial deformation</td>
<td>10^4 to 1000 μm/s</td>
<td>Failure envelope.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 to 70 MPa</td>
<td>Elastic properties.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Consolidation.</td>
</tr>
<tr>
<td>Fault Zone Material, Mineralogy</td>
<td>ODP samples</td>
<td>Core from ODP legs 146, 156, 170, 190, and 205. Accretionary wedge material, decollement material, fault gouge.</td>
<td>Frictional constitutive properties.</td>
</tr>
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<td></td>
<td>Intact samples from Kodiak and the San Gregorio Fault.</td>
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<td>Spatial distribution of shear.</td>
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<td></td>
<td></td>
<td></td>
<td>Consolidation.</td>
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<td></td>
<td></td>
<td></td>
<td>Porosity.</td>
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<tr>
<td>Hydraulic</td>
<td>Fluid flux</td>
<td>10^4 to 2.0 cm^3/s</td>
<td>Permeability. Poro-elastic constants.</td>
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<tr>
<td></td>
<td>Mean fluid pressure</td>
<td>0.5 to 70 MPa</td>
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<td></td>
<td>Fluid pressure differential</td>
<td>0.01 to 50 MPa</td>
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<tr>
<td></td>
<td>Fluid saturation</td>
<td>0-100%</td>
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</tbody>
</table>

Table 1. Experiments will relate prescribed test variables of thermal, mechanical, material, and hydraulic conditions, to complementary observed outputs. Thermal conditions are prescribed by the congruent temperatures of both the sample and the influent fluid. Effective normal stress and strain rate and shear stress and strain rate comprise two sets of complementary paired variables – either component of stress or strain-rate may be prescribed independently, and the complementary variable measured in response. Flow-through tests are facilitated through in-plane injection of the reactant solution (H_2O, brine) under prescribed pressure drop or flow rate, and the complementary variable recorded.

We propose to test hypotheses for the upper stability transition by conducting carefully controlled laboratory experiments on natural and synthetic samples over P-T, fluid, mineralogical, cementation, and compaction conditions that span the stability transition. A key goal of the laboratory work will be to isolate the effect of lithification state on strain localization and frictional behavior. We anticipate that the proposed friction experiments will provide a test of the primary hypotheses for the updip limit of the seismogenic zone of subduction megathrusts.

Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting p. C-14
7. Anticipated Results

This study will produce the first truly integrated dataset on physical properties and frictional behavior in this setting. The dominant hypotheses for stability transitions will be tested. The sensitivity of stable vs. unstable frictional behavior to the parameters discussed above will be documented. Methods for the study of natural fault samples obtained through drilling will be developed and tested; we see this as a crucial preparatory step for the major investment IODP, Earthscope, and ICDP will make in fault zone drilling. Results of the present study will help maximize the data return from such efforts in the future. Detectability of key properties of fault zone and wall rock related to this transition will be tested through exploration of seismic properties.

8. Results of Prior NSF Support


This work was designed to investigate the microphysical processes of rate- and state-dependent friction behavior in simulated granular fault gouge. We studied the effect of relative humidity (<5% to 100%) in velocity stepping tests (10-20 μm/s) and slide-hold-slide (SHS) tests (3-1000 s) on 1-4 mm thick layers of quartz and alumina powders sheared at 25 MPa normal stress. Granular powders were conditioned in situ under controlled RH to create new surface area before shearing. We find a transition from velocity-strengthening frictional behavior to velocity-weakening friction as RH increases. The transition occurs at 30-35% RH for quartz and 55-60% RH for alumina. Frictional healing is negligible at low humidity and increases with increasing RH for both materials. The coefficient of sliding friction is independent of humidity. Our data show that rate- and state-dependent friction behavior for granular materials, including time-dependent healing and steady-state velocity dependence, is the result of chemically assisted mechanisms that can be reduced or turned off at low humidity at room temperature in quartz and alumina. We interpret the dependence of healing on RH to be the result of chemically-assisted mechanisms that strengthen contact junctions. Alumina forms a weak surface layer under high RH that may undergo time-dependent deformation. In quartz powder, contact junctions at the plastic yield stress may undergo hydrolytic weakening leading to greater asperity deformation and increased real area of contact. Hydrogen bonding and desorption of water at the contact junction are two important mechanisms for generating rate- and state-dependent friction behavior in geologic materials. This funding supported 4 graduate students, 2 undergraduate students and publications that include 9 papers and 12 abstracts.


This project supported PhD student Patrick Fulton for the first three years of his graduate research. He has used numerical models to (a) test existing hypotheses explaining fluid overpressures along the San Andreas Fault (SAF), and (b) constrain frictional heat generation along the SAF using models of coupled groundwater flow and heat transport. These simulations incorporate 3-D topographic corrections to the heat flow data, and heterogeneous subsurface permeability structures that include a range of plausible fault permeability architectures, as well as some simplified distinct structural elements that may impact fluid flow (such as a tabular serpentinite body NE of the San Andreas). Our work has shown that heat advection via topographically-driven groundwater flow is not sufficient to obscure a frictionally generated heat anomaly, supporting interpretations that the SAF is anomalously weak. The results of implementing dehydration-driven fluid sources from Franciscan pelites and metabasalts (generated by heating in the wake of the migrating Mendocino Triple Junction) into a regional fluid flow model indicate that these sources are sufficient to drive regionally elevated fluid pressure in some scenarios, but, importantly, severe localization of fluid pressure along the SAF is highly unlikely. Further, the modeling results demonstrate that even for scenarios that can generate regionally elevated fluid pressures, the pressures dissipate within ~200 km of the triple junction, and thus are unlikely as a mechanism to cause fault weakness throughout the SAF system. Publications from this research include 4 papers and numerous abstracts; 2 additional papers are in preparation as Fulton completes his work on the project.

Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting  p. C-15
References Cited:


Dieterich, J.H., 1981, Constitutive properties of faults with simulated gouge, in Mechanical behavior of crustal rocks; the Handin volume (Carter, N.L., et al., Eds.), Geophysical Monograph, no.24, p.103-120.


Lohr, M., Yamagata, T., and Moore, J.C., 1999, Structural fabrics and hydrocarbon content of the San Gregorio Fault Zone, Moss Beach California, in R. E. Garrison, Aiello, I., Moore, J. C. (Eds.), Late Cenozoic fluid seeps and tectonics along the San Gregorio Fault zone in the Monterey Bay Region, California, GB-76, 21-34, American Association of Petroleum Geologists, Pacific Section, Bakersfield CA.
Lupo, T., and Tobin, H., 1999, Seismic velocity in artificial shear zone analogs in sediment: Application to accretionary prism decollement zone imaging, EOS Transactions, American Geophysical Union, v. 80, no. 46, p. F553.

Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting ... p-3


Sakaguchi, A., 1999, Thermal maturity in the Shimanto accretionary prism, Southwest Japan, with the thermal change of the subducting slab; fluid inclusion and vitrinite reflectance study, Earth Planet Sci. Lett., v. 173, p. 61-74.


Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting... p-5

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*Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting … p-6*


Marone and Saffer, Proposal to NSF 8/06, The Transition From Seismic to Aseismic Faulting... p-7