Plate-rate experimental deformation: Aseismic, transient or seismic fault slip

PREDATORS

Introduction

Large magnitude earthquakes are one of the world's greatest risks to human life and damage to infrastructure and economy in densely populated regions. Such large and damaging earthquakes are a historical as well as global phenomenon, with records dating as far back as 684 AD in Japan (Ando, 1975) and paleoseismicity records covering ~8000 years in New Zealand (Berryman et al., 2012). The largest earthquakes occur at convergent margins, near heavily populated areas such as Japan, New Zealand, Indonesia, and the entire west coast of the United States, Canada, and Central and South America. While earthquakes on transform margins or intercontinental regions may not be quite as large, they may still cause great damage and loss of life as occurred during recent events in Italy, Turkey, Taiwan, and Nepal. The hazard is compounded by the fact that these events can cause other natural disasters such as enormous tsunamis, many of which are larger than expected (Polet and Kanamori, 2000) and landslides (Rodríguez et al., 1999). Recently, earthquakes induced by humans, for example from wastewater injection associated with oil and gas extraction, have become a source of concern to the public (Keranen et al., 2013).

Seismologic and geodetic evidence has shown that many large earthquakes tend to be concentrated in certain areas, generally on plate-boundary fault zones and within a discrete depth range known as the "seismogenic zone" which broadly occurs at ~5-35 km depth but these boundaries can vary depending on thermal conditions, fault type (i.e., subduction or strike-slip) and many other factors (Marone and Scholz, 1988; Hyndman et al., 1997). In fact, despite broad observational patterns such as the seismogenic zone, the slip behavior of faults is quite heterogeneous. This is demonstrated by the wide range of seismic coupling, or the proportion of plate convergence that occurs as earthquakes, in subduction zones (Peterson and Seno, 1984; Pacheco et al., 1993). Furthermore, within the seismogenic zone the percentage of the fault surface that ruptures as earthquakes may also vary substantially (Kanamori, 1986). Major faults may also have extensive creeping portions, which can slip without significant seismicity. The most well-known of these is the central San Andreas Fault in southern California (Irwin and Barnes, 1975), but other examples include the North Anatolian Fault in Turkey (Cakir et al., 2005) and the Longitudinal Valley Fault in Taiwan (Hsu and Bürgmann, 2006). Furthermore, fault slip is not restricted to earthquakes and creep, but may also occur as discrete slow events that may be slightly faster than plate convergence rates but are much slower than ordinary earthquakes (Ide et al., 2007; Peng and Gomberg, 2010). Slow fault slip is mostly observed to occur at the base of the seismogenic zone in subduction zones (mostly because of proximity to instrumentation). However, they have also been observed on normal faults in the Italian Appennines (e.g. Amoruso et al., 2002) and on the strike-slip San Andreas Fault (Linde et al., 1996). In certain well-instrumented subduction zones, they have been identified updip of the seismogenic zone. One such area is the Nankai Trough, where low frequency and very low frequency earthquakes (LFE and VLF) were located within the accretionary prism at shallow depths, likely on splay faults (Ito and Obara, 2006). There is also evidence of shallow slow slip events occurring offshore Costa Rica from borehole strainmeters and GPS data (Brown et al., 2005; Davis et al., 2011). Some geodetic observations indicate that slow fault slip tends to occur near the limits of the seismogenic zone and therefore may delineate earthquake rupture areas (Chapman and Melbourne, 2009), but Ito et al. (2013) documented slow earthquakes well within the rupture area of the 2011 Tohoku earthquake.

Collectively, current knowledge indicates that while most large earthquakes occur at plate boundaries and within a certain depth range, *the slip behavior of faults, from stable creep to slow slip events to earthquakes, varies widely in space and time and is difficult to predict.*

State-of-the-Art: Laboratory Studies of Fault Slip Behaviour

Because direct observation and sampling of natural faults is limited to a few km depth, quantitatively evaluating fault slip behavior relies on direct testing of both natural and analogue fault materials in laboratory shearing experiments. In the laboratory, fault behavior is simulated by shearing geologic materials and measuring the shear strength. Because the shear strength strongly depends on the normal load, it is more useful to describe the strength of geologic materials with coefficient of friction μ:

$$\tau = \mu\sigma_n' + c \qquad (1)$$

Where σ_n' is the effective normal stress (total normal stress minus pore fluid pressure), and c is the cohesion (e.g. Handin, 1969). It is also common to neglect the cohesion, so that shearing experiments are assumed to specifically measure changes in frictional behavior via μ.

In an early study, Byerlee (1978) noted that a wide range of geologic materials seemed to exhibit the same strength, with μ being approximately 0.85 (0.6 for normal stresses above 200 MPa). Subsequent studies has shown that this is an oversimplification, and that in fact friction coefficients for natural earth materials can range down to as low as < 0.1. Strength is highly dependent on the mineralogy, with many weak materials having a high phyllosilicate mineral content. Basic measurements of μ provide information about the strength of the faults and the surrounding crust and maximum stress levels on faults, but provide little information about the mechanisms behind earthquakes themselves.

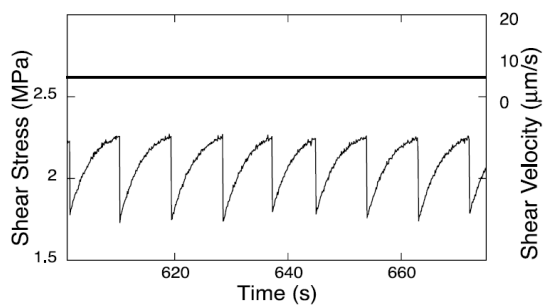
One particularly important early observation was that some geologic samples exhibited a jerky, intermittent style of slip termed "stick-slip" which was suggested to be an analogue of repeating earthquakes (Brace and Byerlee, 1966). Not all materials exhibited such behavior; indeed the frequency and violence of the stick-slips was found to be heavily dependent on mineralogy/rock type (Figure 1) (e.g. Brace, 1972; Shimamoto and Logan, 1981). Interestingly, these stick-slip events spontaneously occur although a constant driving velocity is enforced as a boundary condition. This due to the finite stiffness of testing apparatuses which allows a portion of the deformation is taken up by the apparatus itself, thus the sample does not necessarily shear at the prescribed rate but can oscillate between a true velocity of zero (stick) and a much higher velocity (slip) (Cook, 1981).

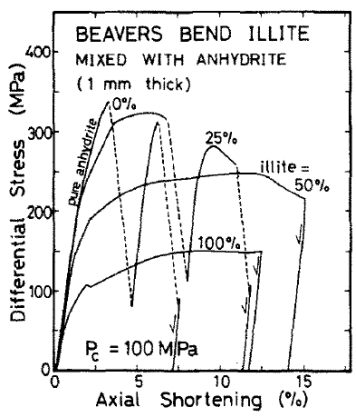
Because stick-slip spontaneously appears (or sometimes does not appear), in friction experiments, little was known about the earthquake nucleation process. Better understanding came with the recognition that frictional strength is not constant but depends on both time and driving velocity. Friction time dependence is measured in the "slide-hold-slide" (SHS) test, where the sample is intermittently sheared and held at zero driving velocity for a controlled period of time. Upon re-shear following the hold period, a distinct peak in shear strength is commonly observed which depends on the length of the hold time (Dieterich, 1972). These tests show how the static strength of faults increases in the interseismic period, providing a mechanism for repeated earthquake rupture in the laboratory and nature. Even more important was the development of the velocity-step test, in which the testing machine-controlled sliding velocity is suddenly increased and its effect of on sliding friction is observed. The frictional response to a velocity step is described with a set of empirically-derived constitutive laws known as rate- and state-(dependent) friction (RSF) laws (Dieterich, 1979; 1981). In their simplest form, these laws quantify the change in fault strength with the parameter *a-b*:

$$a - b = \frac{\Delta\mu_{ss}}{\Delta \ln(V)} \qquad (2)$$

Where μ_{ss} is the coefficient of friction at steady state (i.e., constant with displacement or shear strain) and V is the driving velocity. As applied to tectonic faults, a positive value of *a-b* (friction increase following a velocity increase) describes velocity-strengthening behavior that is favorable for steady fault creep. A negative value of *a-b* (velocity-weakening behavior) results in a force imbalance which is a necessary condition for unstable slip; such slip instability allows a stress drop and acceleration to coseismic slip rates (Marone, 1998; Scholz, 2002). The observation of stick-slip in the laboratory is a direct consequence of

Figure 1: Stick-slip behaviour in glass beads (left, Marone and Savage, 2007) and anhydrite mixed with illite (right, Shimamoto and Logan, 1981). Note that illite reduces stick-slip behavior.





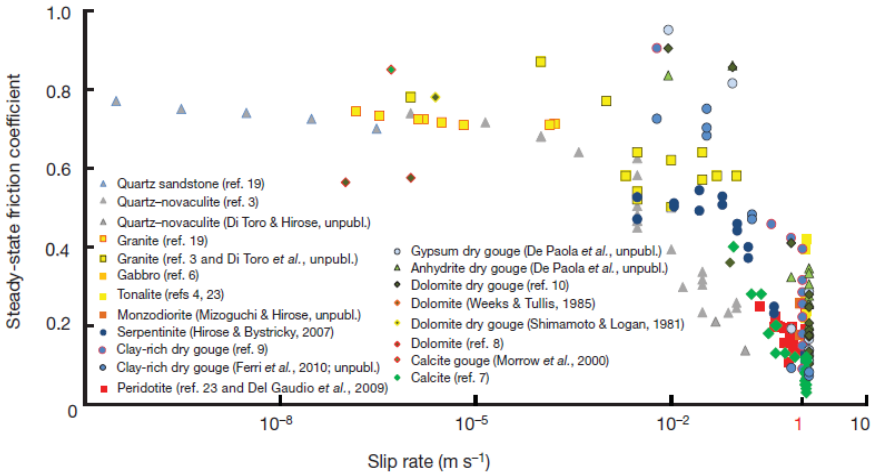


Figure 2: Friction experiments for a range of materials at up to m/s slip velocities. Note the lack of data below 10^{-7} m/s. From Di Toro et al. (2011).

velocity-weakening friction combined with sufficient compliance (i.e. low stiffness) of the testing apparatus, or wall rock in the case of natural faults, which allows the force imbalance to occur (Cook, 1981; Gu et al., 1984; Scholz, 1998). Most studies using RSF are typically conducted at slip velocities in the µm/s to mm/s range, much slower than coseismic slip rates during earthquakes which are estimated to be approximately 1 m/s (Brune, 1970; Heaton, 1990). Recent efforts to simulate such rapid motion has led to the development of high-velocity friction experiments, which can simulate coseismic fault slip at speeds in excess of 1 m/s (Tsutsumi and Shimamoto, 1997; Di Toro et al., 2011). These studies have demonstrated that extreme weakening is ubiquitous at high velocity (Figure 2).

Identifying the mechanisms responsible for observations in the laboratory is an ongoing challenge. At high velocity, flash melting, silica gel development, thermal pressurization, or dehydration embrittlement may be active (Di Toro et al., 2011). The cause of velocity-weakening behaviour at intermediate velocities appears to be complicated. Some studies show that the development of shear localization features observed in post-experiment microstructural analyses is associated with slip instability (Logan et al., 1992). Other studies suggested that unconsolidated, granular gouge inhibits stick-slip that occurs on intact rock surfaces (Byerlee and Summers, 1976); in combination with seismological observations of depth-dependence in seismicity (Marone and Scholz, 1988) this has led to the popular hypothesis that processes associated with sediment lithification at elevated pressure and temperature are responsible for slip instability (Moore and Saffer, 2001; Moore et al., 2007). These are numerous and include mineral dehydration, diagenetic mineral transformations, enhanced porosity loss, intergranular cementation, and dissolution-precipitation reactions. This is consistent with the observation that velocity-weakening in some materials is favored at temperatures of a few hundred °C (Blanpied et al., 1998; den Hartog and Spiers, 2013), corresponding to depths of several 10's of km. A key general observation is the tendency for rock or sediment composed of phyllosilicate minerals (clays and micas) to be weak and velocity strengthening, while other minerals (e.g. quartz, feldspar, calcite) tended to result in velocity weakening or stick-slip (Brace, 1972; Shimamoto and Logan, 1981; Scruggs and Tullis, 1998; Brown et al., 2003; Ikari et al., 2009, 2011). Which factors are most important is still under debate.

Finally, in addition to ordinary earthquakes, slow and transient slip events or "slow earthquakes" have been observed, many of which have slip velocities events that do not exceed ~100 nm/s (10^{-7} m/s) but for some events such as LFE or VLFE may be up to 0.05-2 mm/s (Ito and Obara, 2006; Ide et al., 2007; Peng and Gomberg, 2010). Slow slip occurs on several plate boundary faults and therefore must be controlled by frictional mechanisms (Brown et al., 2009), however little is known about their generation. Numerical modeling studies have simulated slow slip using RSF data from intermediate-velocity friction measurements of analogue materials, such as halite, granite or gabbro (Shibazaki and Shimamoto, 2007; Liu and Rice, 2009). These studies suggest that slow earthquakes may arise from "conditional stability" associated with areas where frictional behaviour is on the boundary between velocity weakening and strengthening. Laboratory studies specifically targeting slow earthquake generation are thus far sparse.

Limitations in Current Knowledge: The Case for Low-Velocity Friction Experiments

Despite the many advances in knowledge over the years, it must be recognized that tendency for faults to host earthquake slip (or not, in the case of creeping faults) is far from well understood. In fact, despite the increasing complexity in experiments and numerical models, the scientific community is hardly closer to predicting earthquakes in a meaningful way. This is illustrated, unfortunately, by several recent unexpected and disastrous earthquakes such as 2009 L'Aquila, 2011 Christchurch, and 2011 Tohoku earthquakes. One particularly glaring example is the Parkfield region on the San Andreas Fault in California. Based on a regular occurrence of M_w = 6 earthquakes, the next event was predicted to occur in

the early 1990's. The next earthquake actually occurred in 2004, and although a wealth of information was obtained from this event the prediction experiment is widely considered a failure (Bakun et al., 2005).

Similarly, from a laboratory standpoint, despite the increasing sophistication in experimental techniques and equipment there remain several serious knowledge gaps. A particular problem is that velocity-weakening friction is actually infrequently observed, and mostly for hard rocks or sediment composed of strong minerals (quartz, powdered granite, calcite). However, field studies including several scientific drilling projects targeting major fault zones and field studies of surface exposures (e.g. Vrolijk and van der Pluijm, 1999; Underwood, 2007) have shown that fault cores which accommodate slip are ubiquitously rich in phyllosilicate minerals. Friction studies have shown that phyllosilicates are predominantly velocity strengthening; this frequently measured velocity strengthening seems inconsistent with the frequent seismicity on plate-boundary faults. This point, and also the lack of consensus on why earthquakes occur, suggests that a fundamental piece of information is missing from our understanding of fault slip behaviour. **In this proposal, I suggest that this missing fundamental piece of information is how faults slip when driven at plate-convergence slip rates.**

Two specific shortcomings in current lab studies are identified here and targeted for study. First, an overwhelming majority of experimental studies using RSF are performed at intermediate driving velocities of ~10^{-7} to 10^{-4} m/s (or roughly a µm/s to mm/s range). This is too fast to simulate plate convergence rates of several cm/yr, or on the order of ~10^{-9} m/s (nm/s range) (e.g. DeMets et al., 1990). Similarly, the applicability of high-velocity friction experiments is limited to cases where an earthquake has already nucleated and little information is gained regarding how and why some fault areas are able to generate dynamic fault slip. Surprisingly little information has been obtained through friction experiments where the slip velocity is slower than ~10^{-7} m/s (e.g. Figure 2), and then only for analogue materials such as granite, calcite or halite/muscovite mixtures rather than natural fault gouges (e.g. Blanpied et al., 1987; Weeks, 1993; Niemeijer and Spiers, 2005). However, plate convergence velocities are perhaps the most important factor controlling fault slip behaviour because they represent the boundary condition for slip on plate-boundary faults. *Friction experiments conducted at plate-convergence driving rates may reveal widespread frictional instability that explains the similarly widespread occurrence of (both fast and slow) earthquakes on plate-boundary faults.*

Secondly, although previous experimental studies have established that fault strength depends on both velocity (via velocity-step tests) and time (via SHS tests), these ideas have not yet been effectively combined and applied to natural faults. SHS tests utilize a zero driving velocity condition to simulate interseismic periods, but due to finite apparatus compliance the sample relaxes resulting in a decreasing shear stress and a decreasing but non-zero real fault slip rate. While this may simulate a specific situation such as postseismic slip, if the behaviour of seismogenic faults is similar to stick-slip behaviour in the laboratory, then the fault is being loaded (shear stress is increasing) throughout the interseismic period. SHS tests therefore may not be a realistic or representative situation because natural faults are still being driven at all times at a tectonic convergence rate which does not decrease to zero, while the fault zone itself may be locked or partially locked. Furthermore, in the example of stick-slip it can be seen that a steady state is rarely achieved (Figure 1); therefore RSF analyses, which require that the parameter *a-b* be evaluated at steady state, are of limited applicability. On real faults, shear loading driven at tectonic convergence rates during the interseismic period would therefore be slow enough to allow time-dependent mechanisms to operate and strengthen the fault, allowing elastic strain energy to be stored for release in a future event. These mechanisms may include pressure solution, grain cementation, or secondary consolidation, which require very long timescales and whose effects are disrupted or destroyed by shear failure (i.e., frictional sliding). *It is suggested here that long-term shear loading driven by slow, plate convergence rates is more representative of real faults and captures interseismic strengthening effects which intermediate- to high-velocity experiments cannot.*

As an example of the enormous potential that slow, plate-rate laboratory experiments offer, consider the Japan Trench subduction zone, which hosted the 2011 M_w = 9 Tohoku earthquake. A recent set experiments was performed using samples of the plate-boundary fault zone in the Tohoku region recovered by scientific drilling (Ikari et al., 2015). Originally designed to simply measure the interseismic shear strength of the fault material under in-situ conditions of the borehole, shearing at the convergence rate between the Pacific and North American (or Okohtsk) plates of 8.5 cm/yr revealed small stick-slips, observable instances of unstable slip. Another key unexpected result is the spontaneous appearance of irregularly and infrequently occurring transient slip events, which consisted of a stress drop of 50-120 kPa (3-6% of the shear strength) which persisted over 2-4 hours accompanied by a clear peak in slip velocity of up to ~25 cm/yr during the stress drop (Figure 3). These events are laboratory-observed slow slip events analogous to those observed in several subduction zones worldwide and were not observed in experiments

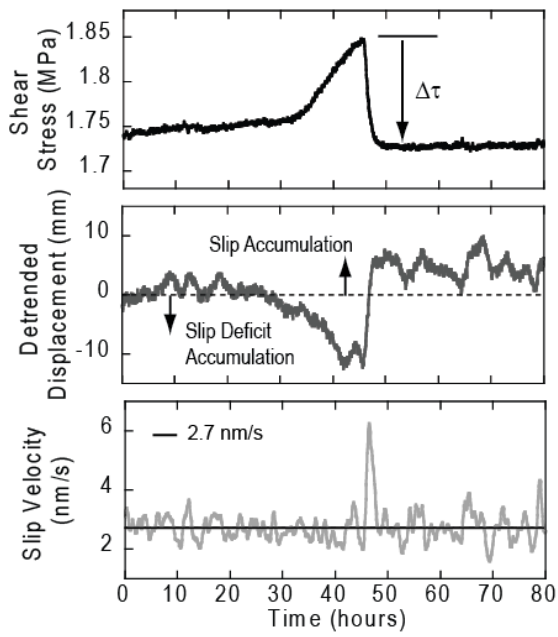


Figure 3: Example of data from a laboratory-observed slow slip event in a sample from the Tohoku fault zone, including stress drop, slip deficit/recovery, and peak slip velocity. From Ikari et al. (2015).

using the same material at driving velocities higher than the plate rate. These unique results clearly demonstrate that, when the plate convergence rate is enforced as a boundary condition, the Tohoku fault gouge is weak, velocity-weakening, and exhibits instances of slip instability in the form of small stick-slips and slow slip events. It is important to note that none of these behaviours would have been predicted from intermediate to high-velocity friction data, but the shallow Tohoku megathrust exhibits both slow slip events (Ito et al., 2013) and of course the immense amount of shallow coseismic slip during the 2011 Tohoku earthquake which are consistent with frictional slip instability.

PREDATORS Project Objectives and Research Strategy

Although research on fault slip behaviour over the years has revealed much about how and why earthquakes occur, there remain several fundamentally important knowledge gaps. There are two primary, overarching goals of the PREDATORS project:

(1) Quantitatively describe the slip behaviour of geologic materials –both natural and analogue fault rocks – <u>when driven at plate tectonic convergence rates as they are in nature</u>, in order to explain seismologic and geodetic observations on real faults and predict fault slip behaviour in the future.

(2) Identify the important factors controlling the range of observed modes of fault slip. Which processes (or lack thereof) or material characteristics are important for causing aseismic creep, slow slip events, or locking and coseismic slip?

Within this framework, a specific research strategy will be implemented to best accomplish these two main goals. Some key considerations of this strategy include:

Samples:

Rock and mineral standards (e.g granite, quartz silt, or source clays) are necessary to thoroughly document plate-rate frictional behaviour over a wide range of compositions. Because natural fault rocks are mineralogically complex, monomineralic standards are essential for providing a framework within which frictional behaviour in general may be understood and predicted.

A special focus will be placed on samples recovered from scientific drilling projects targeting major faults. The PI has access to several natural samples obtained by scientific drilling in Integrated Ocean Drilling Program (IODP), Ocean Drilling Program (ODP), and International Continental Drilling Program (ICDP) projects, as well as other various expeditions. Many of these samples are from active subduction zones such as the Nankai Trough (Japan), the Tohoku region of the Japan Trench, Costa Rica, Barbados, Mediterranean Ridge, and Chile, but also from rift zones such as the Woodlark Basin (Papua New Guinea). Samples from onshore fault zones include those from the San Andreas Fault (California) via the San Andreas Fault Observatory at Depth (SAFOD) and the Alpine Fault in New Zealand via the Deep Fault Drilling Project (DFDP). With the exception of SAFOD, almost all of the samples were recovered from very shallow (< 1 km) depth, thus in-situ conditions are easily simulated in the laboratory. The PI is highly involved with IODP as both a participant and project proponent, and thus anticipates future access to drilling samples, including planned expeditions to the Japan Trench, Hikurangi margin, and Sumatra.

While rock and mineral standards are crucial for identifying general and widely applicable frictional behaviour, natural samples are appropriate for focused, site-specific problems. Some of examples of these which can/will be addressed by the PREDATORS project may include:

Japan Trench: The 2011 Tohoku earthquake generated up to 80 m of coseismic slip that reached the seafloor at the Japan Trench (Fujiwara et al., 2011; Ito et al., 2011). Furthermore, the fault patch which

ruptured during the Tohoku earthquake also experiences slow slip events, one of which was likely ongoing at the time of the earthquake (Ito et al., 2013). Is the entire megathrust up to the trench prone to instability?

Nankai Trough: Unlike the Japan Trench, coseismic slip reaching near the trench during recent M_w = ~8 earthquakes is estimated to be only a few meters, if any at all. Does the shallow megathrust have the potential for slip instability that has not yet been identified? Can the frictional properties of Nankai fault material explain the occurrence of low-frequency earthquakes?

Costa Rica: This subduction zone is characterized by a large amount of heterogeneity in subducting mineralogy and topography, specifically seamounts exposing nannofossil chalk at the seafloor (Spinelli and Underwood, 2004). Furthermore, heat flow measurements indicate significantly lower temperatures than other margins (e.g. Harris et al., 2010). How do these characteristics influence seismicity in this region?

Barbados: Like some other plate-boundary fault zones (e.g. Japan Trench, San Andreas Fault) the plate-boundary megathrust is rich in the weak, water-attracting clay mineral smectite. Are the slip characteristics of fault material from this region consistent with other major fault zones of similar composition?

San Andreas Fault: Although a major plate-boundary fault zone, the San Andreas Fault is known for a large creeping zone and regions of microearthquakes. Can the causes of this behaviour be explained by laboratory data?

Alpine Fault: Various lines of evidence suggest that this fault is late in its seismic cycle, and moreover appears to be locked up to the near surface. Is the Alpine Fault frictionally unstable to shallow depths, and what are the mechanisms that cause this material to be prone to locking?

Woodlark Basin: In the Woodlark Basin, rifting at a rate of 3.7 cm/yr has caused the development of a seismogenic detachment fault. How do the friction systematics on normal faults compare with subduction thrusts or transform faults?

Sumatra: Like the Japan Trench, Sumatra has experienced great, M_w = ~9 earthquakes. Does the Sumatra fault material exhibit specific behaviour or characteristics that can be used to identify other regions in danger of great earthquakes?

Hikurangi: Unlike many subduction zones, the Hikurangi margin is not known for large, repeated earthquake rupture but rather slow slip events. What gouge properties are favourable for slow slip events as opposed to coseismic rupture?

Equipment:

An advantage of the MARUM Geotechnics Laboratory is the availability of multiple shearing devices appropriate for fault zone studies (e.g. Kopf, 2013; Ikari et al., 2015; Trütner et al., 2015). Therefore, the PREDATORS project will employ an "overlapping complexity" strategy where data collection can begin immediately using established experimental protocols on certain devices, while modification of other devices for more advanced testing can occur concurrently. This also helps offset the long duration of experiments due to using slow rates. More complex, ambitious and cutting-edge testing (for which the success rate may not be as high) will be phased in. The level of experimental complexity during the lifetime of the project can therefore be adjusted according to the technological development of the apparatus modifications. The end result is that productivity of the project will not be limited by unpredictability in machine development.

Collaborations:

In order to ensure wide applicability of the results obtained during the PREDATORS project, collaborations outside of MARUM will play an important role. With regard to this aspect, the PI will make use of a wide range of long-standing collaborations with highly-regarded scientists in all relevant fields. The most obvious avenue for collaboration is a standing exchange of ideas and visits with other rock mechanics labs, which will advance both scientific knowledge and technical aspects of laboratory testing. Other important collaborations will be initiated with those outside of the experimental community. This includes working with observational geophysicists to design experiments to test specific hypothesis matching seismologic and geodetic observations of fault slip; and also comparing laboratory phenomena (e.g. stick-slip or slow slip) with real-fault observations. Examination of sheared laboratory samples is of great interest to structural geologists, who have long sought to identify seismic slip in the rock record (Cowan, 1999). Finally, experimental data is necessary to constrain numerical models of all types of fault slip, including simulations of slow slip events which currently lack appropriate constraints.

Section b. Methodology

Current Laboratory Capabilities

The Marine Geotechnics laboratory at MARUM is equipped with several rock/sediment deformation apparatuses, including three Giesa single-direct shear apparatuses, two Wykeham-Farrance rotary shear devices, and a proprietary high-pressure high-temperature single-direct shear device HYDSPA (Figure 4). Initially, experiments will be conducted in the Giesa direct shear apparatuses, which have already been successfully utilized in a first set of plate-rate experiments on samples from the Tohoku region of the Japan Trench (Ikari et al., 2015). In this device, the sample cell is a stack of two steel plates which house the cylindrical sample. Normal load is applied to the top face of the sample with a vertical ram, and the lower plate is displaced horizontally relative to the top plate by an electric motor, inducing planar (i.e. localized) shear deformation in the sample. The device is proven capable of employing shearing at rates at least as low as ~5 cm/yr, satisfactorily matching a large number of plate tectonic slip rates (e.g. DeMets et al., 1990). For example, in order to generate a driving velocity of 8.5 cm/yr (the rate in the Japan Trench and Costa Rica), the apparatus utilizes a stepper motor with an update rate of 0.19 Hz and a step width of 0.015 µm; recorded data at 0.033 Hz (or 10 measurements every 0.81 µm defined by the displacement sensor resolution) results in a time-averaged displacement rate of 2.7 nm/s (= 8.5 cm/yr). However, the convergence rate at some plate boundary faults are sufficiently slow that they are at not yet proven to be within the capability of the apparatus. This includes important fault zones such as the San Andreas Fault in California and the Alpine Fault in New Zealand (both ~2.5 cm/yr; Norris and Cooper, 2000; Titus et al., 2005). Therefore, there is a need for further technical development in order to match convergence rates for slower faults. Furthermore, implementation of slip rates slower than the far-field plate convergence rates are important for specifically targeting the behaviour of faults that are locked or partially locked. Both the Giesa direct-shear and the rotary shear devices are appropriate for low (room temperature) and low pressure (< 20 MPa) conditions, however the Giesa devices are preferable for this study due to: (1) easily measureable apparatus compliance, and (2) the ability to measure both the driving velocity (far-field driving rate) and the true sample displacement.

The HYDSPA system is capable of normal stresses of up to 200 MPa and temperatures of up to 240°C. This apparatus consists of a sturdy load frame, two powerful low-friction hydraulic pistons (one vertical, one horizontal), and an external heating chamber which houses the sample cell. The design of the device and sample holder are similar to that of the Giesa devices. The holder is fitted into a heavy-duty roller gear device capable of moving effective loads of several tons at almost negligible friction. Within the sample cell, an O-ring seal to confines the pore fluid on the sample surface (Figure 4). Three ports installed in the lower half allow pore pressure measurement; one port accesses the bottom of the sample and is designed to record fluid pressure rise during (vertical, or normal) loading, i.e. the backpressure. Another port monitors fluid pressure on the actual shear surface, and is isolated from the other fluid ports and areas of the sample chamber. The apparatus is currently configured for pore pressure monitoring without control, although the maximum pore pressure can be limited by manually venting the pore fluid. Temperature is permanently monitored via a fourth access port and is instrumented with a thermistor. <u>In its present state, this device is capable of producing excellent friction data using conventional velocity-stepping procedures</u> within the velocity range of 0.1-100 µm/s (10^{-7}-10^{-4} m/s) (Trütner et al., 2015), which is comparable with most established friction data produced over the last ~20 years. This device will need modification in order to shear at sufficiently slow rates and also to measure the true sample offset at the sample holder. However, the technical hurdle of conducting shearing experiments at high pressure, high temperature and with pore fluids has already been overcome for this device. Therefore, relevant friction data sheared at a plate-rate boundary condition may be collected at conditions appropriate for well within the seismogenic zone (corresponding to approximately 10-15 km, depending on assumed P-T gradients).

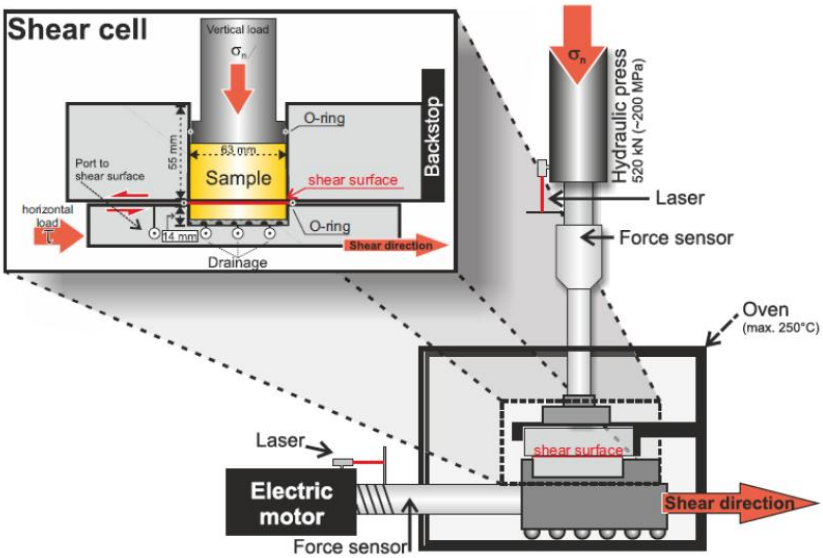


Figure 4: Schematic illustration of the HYDSPA system in the MARUM laboratory (from Trütner et al., 2015)

Education and Outreach

It is anticipated that much of the experimental work and interpretation will be carried out as Ph.D. and Master degree student projects. This will provide students with hands-on training in experimental techniques and data analysis in a state-of-the-art laboratory facility. The PI has extensive experience in experimental laboratories worldwide via multiple international collaborations; this will help ensure that the geotechnical laboratory at MARUM will stay at the forefront of experimental research and provide students with the opportunity for inter-laboratory collaboration abroad. Research results will be disseminated via participation in major annual conferences (American Geophysical Union and European Geophysical Union) and smaller workshops. MARUM also has a dedicated outreach group which is a valuable resource for publicizing important research, for example via press releases and web videos.

Educational opportunities will not be limited to the laboratory; due the PI's heavy involvement in ICDP and IODP drilling projects, students will have the opportunity to be on-site participants. One potential example is the follow-up to the Japan Trench Fast Drilling Project (JFAST) called JTRACK in the Tohoku earthquake region, for which the PI is a member of the proponent team. Additionally, many of the drilling projects with which the PI is involved are highly visible (particularly projects in the Nankai Trough, San Andreas Fault, Hikurangi, and the aforementioned JFAST project) and are of great interest to the general public. IODP in particular has an excellent outreach program and is an excellent avenue for communicate hard science to the general public, for example via media visibility or by providing short courses.

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