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SLOW MOTION EARTHQUAKES

Taking the Pulse of Slow Slip with Scientific Ocean Drilling

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Scientists prepare fluid samplers for installation in a borehole observatory at the Hikurangi subduction zone on IODP Expedition 375. *Photo credit: Aliki Westrate, Expedition 375 Outreach and Education Officer*

ABSTRACT. The discovery of a spectrum of slow earthquakes and slow slip events on many of Earth's major tectonic faults has sparked a revolution in the fields of seismology, geodesy, and fault mechanics. Until about 15 years ago, it was believed that faults either failed rapidly in damaging earthquakes or by creeping at rates of plate tectonic motion. However, the widespread observation of episodic, slow fault slip events at plate boundaries around the world, including at subduction zones, has revealed that fault slip behavior spans a continuum of modes, from steady creep to fast, earthquake-inducing slip. Understanding the processes that control these various failure modes is one key to unlocking the physics of earthquake nucleation and slip on faults. Scientific ocean drilling holds a unique place at the forefront of these efforts by allowing direct access to fault zones and sediment in the subsurface where slow slip events occur, by enabling near-field monitoring in borehole observatories, and by providing samples of incoming sedimentary succession that comprises the protolith for material in slow slip source regions at subduction zones. Here, we summarize fundamental contributions from scientific ocean drilling at subduction zones to this emerging field.

INTRODUCTION

Slow slip events (SSEs) involve transient aseismic slip along a fault, lasting days to years, at a rate intermediate between plate tectonic displacement rates (centimeters per year) and the slip velocity required to generate seismic waves (centimeters to meters per second). Installation of dense, plate-boundary-scale geodetic networks in the last two decades has enabled detection of these events, revealing their importance as a significant mode of fault slip. The observation of SSEs and associated seismic phenomena at subduction megathrusts worldwide has created one of the most dynamic fields of research in seismology and geodesy today (e.g., Ide et al., 2007; Schwartz and Rokosky, 2007; Peng and Gomberg, 2010). Although SSEs appear to bridge the gap between typical earthquake behavior and steady, aseismic slip on faults, the physical mechanisms that lead to SSEs and their relationship to the destructive, seismic slip on subduction thrusts remain poorly known.

Evidence for transient creep events on continental faults—such as the San Andreas—has been noted in a few cases for some time (e.g., Goulty and Gilman, 1978; Sacks et al., 1982; Linde et al., 1996), but such events were not well characterized until continuously operating GPS networks began to reveal episodic, aseismic fault slip events at several subduction zone plate boundaries. The first well-documented subduction zone slow slip events were discovered in southwest Japan (Hirose et al., 1999) and Cascadia (Dragert et al., 2001) at locations downdip of areas that are thought to store strain and then slip catastrophically in great earthquakes (so-called "locked zones"). These discoveries were quickly followed by a succession of observations of SSEs at other circum-Pacific subduction zones (e.g., Kostoglodov et al., 2003; Douglas et al., 2004; Sagiya, 2004; Hirose and Obara, 2005; Ohta et al., 2006; Wallace and Beavan, 2006; Outerbridge et al., 2010; Valee et al., 2013; Ruiz et al., 2014). In tandem with the geodetic observations, seismologists recognized the occurrence of tremor at subduction zones, an emergent seismic signal previously associated mainly with volcanic processes (Obara, 2002). This was soon linked spatially and temporally to many geodetically detected slow slip events, and was termed "non-volcanic tremor" (NVT) at first (Rogers and Dragert, 2003; Hirose and Obara, 2005). Coincident tremor and slow slip episodes are now commonly observed at the Cascadia and Nankai Trough subduction zones, and are often called "episodic tremor and slip" (ETS) events. Observations of tremor were followed by recognition of a range of slow seismological expressions of slow slip, including low frequency and very low frequency earthquakes (Shelly et al., 2006; Ito et al., 2007), thought to represent shear slip on the plate boundary (Shelly et al., 2007). These tremor and low frequency earthquakes are typically considered to be part of the spectrum of slow slip event behavior.

SSEs involve a few to tens of centimeters of slip over periods of weeks to years, in some cases releasing accumulated tectonic stress equivalent to that of magnitude 6.0–7.0 earthquakes. The observation that these kinds of slow slip events likely preceded (and perhaps triggered) the 2011 M_w 9.0 Tōhoku-oki (Japan Trench) and the 2014 M_w 8.1 Iquique (Peru-Chile Trench) subduction plate boundary earthquakes (Kato et al., 2012; Ito et al., 2013; Ruiz et al., 2014) provided an impetus to clarify the poorly understood relationship between SSEs and damaging megathrust earthquakes (Obara and Kato, 2016). Most well-studied SSEs occur along the deep end of the earthquake generation zone, for example, below the "seismogenic" zone and at depths greater than 20–30 km (Dragert et al., 2001; Obara et al., 2004; Hirose and Obara, 2005; Ohta et al., 2006; Wallace and Beavan, 2010; Radiguet et al., 2012). However, recent observations indicate that slow slip events are also common to the shallow portions of offshore subduction plate boundaries, at less than 15 km depth (Saffer and Wallace, 2015), and continue to within a few kilometers of the seafloor, possibly all the way to the trench (Wallace et al., 2016; Araki et al., 2017).

Despite the fact that SSEs are now widely recognized to play an important role in the accommodation of plate motion at tectonic boundaries, our understanding of why they occur is largely incomplete. A variety of theories regarding the origin of SSEs have been proposed; most of these consider episodic slow slip as a consequence of low effective stress (due to elevated fluid pressures) within a conditionally stable frictional regime (see reviews in Saffer and Wallace, 2015, and Bürgmann, 2018). These hypothesized mechanisms for SSEs arise from theoretical and modeling studies (e.g., Liu and Rice, 2007) and indirect interpretations of physical properties from seismic imaging of faults known to host slow slip (Kodaira et al., 2004; Audet et al., 2009; Song et al., 2009; Kitajima and Saffer, 2012). Most well-studied subduction zone SSEs occur too deep (>20 km depth) for the high-resolution imaging, direct sampling, and in situ measurements within the SSE source region that are needed to test these ideas. This lack of access has placed inherent limits on our ability to resolve the physical processes and in situ conditions responsible for slow fault slip behavior.

However, shallow SSE regions, where slow slip events occur much closer to Earth's surface (<15 km), may provide the best chance to resolve outstanding questions about slow slip. For example, at the northern Hikurangi subduction zone offshore New Zealand, a recent seafloor geodetic experiment has shown that SSEs can occur to within 2 km of the seafloor, and possibly all the way to the trench (Wallace et al., 2016). The close proximity of SSEs to the seafloor there presents a remarkable opportunity to use scientific ocean drilling to drill into and sample, collect downhole logs, and conduct monitoring in the very near field of the SSE source area. To that end, International Ocean Discovery Program (IODP) drilling took place in 2017 and 2018 at north Hikurangi on Expeditions 372 (Pecher et al., 2018) and 375 (Saffer et al., 2018) (Figure 1a), representing the first IODP effort specifically targeted at resolving

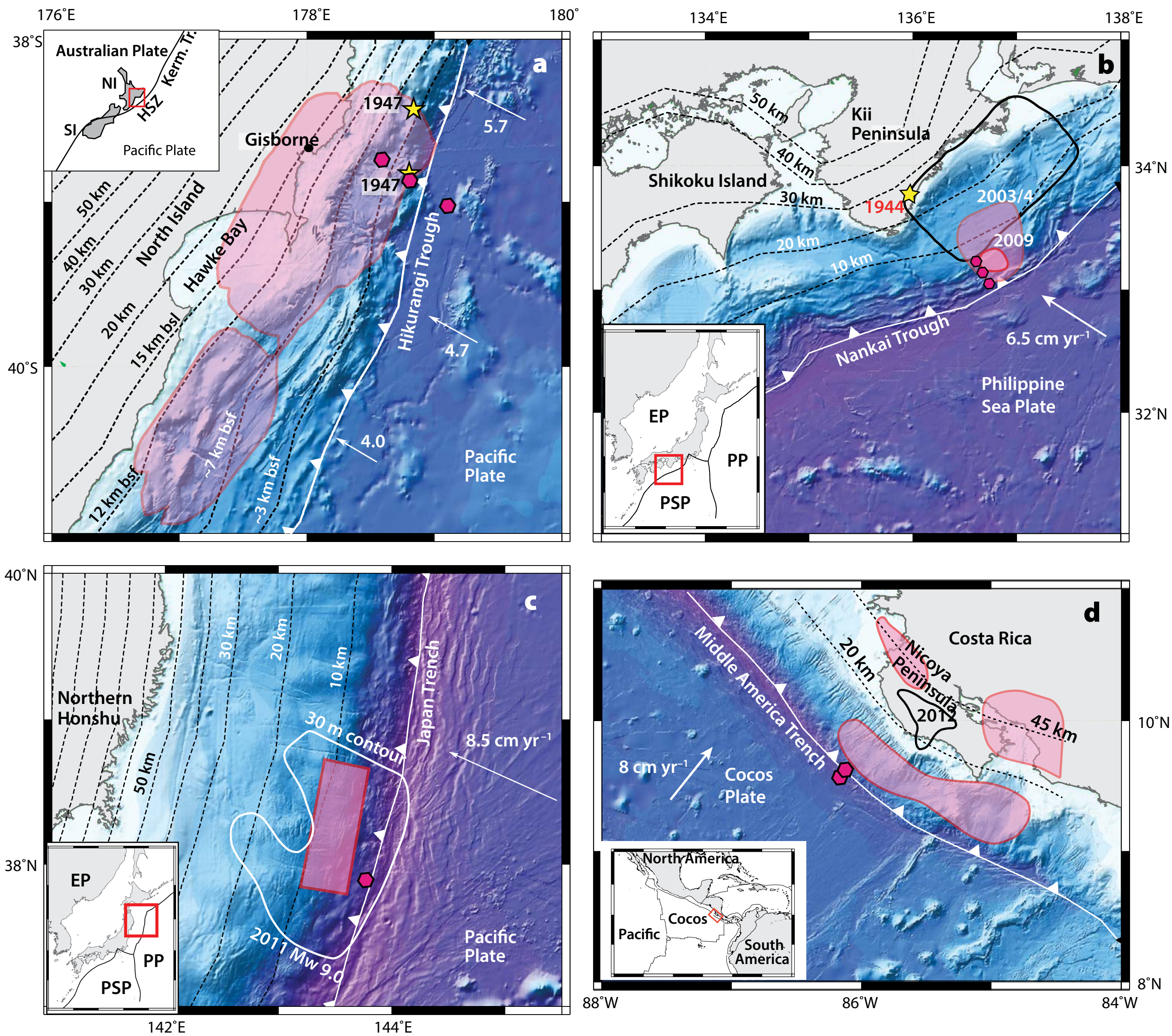


FIGURE 1. Four subduction margins with well-characterized shallow slow slip events (SSEs) and slow earthquakes, where IODP drilling has also taken place: (a) Hikurangi, (b) Nankai, (c) Japan Trench, and (d) Costa Rica. Black dashed contours are depths to the interface (in kilometers below Earth's surface); pink shaded areas show the locations of SSEs and slow (very low frequency) earthquake clusters (Ito and Obara, 2006; Wallace et al., 2012; Dixon et al., 2014; Sugioka et al., 2012; Ito et al., 2013). Black/white solid contours outline slip in previous large plate interface earthquakes at Nankai, Costa Rica, and Northern Japan. Yellow stars show epicenters of historical large subduction interface earthquakes at Hikurangi and Nankai. Pink dots show locations of previous IODP drilling. *Modified from Saffer and Wallace (2015)*

the origins of SSEs. However, shallow SSEs have also been observed at southwest Japan's Nankai Trough (Araki et al., 2017), the Japan Trench (Kato et al., 2012; Ito et al., 2013), and Costa Rica's Middle America Trench (Brown et al., 2005; Davis et al., 2015), where several IODP expeditions have been undertaken over the last 20 years (Figure 1). Although the Nankai Trough, Japan Trench, and Costa Rica scientific drilling efforts were targeted at understanding seismogenic (earthquake generating) processes, IODP drilling data from these regions have provided unexpected new insights into SSE processes. We expect scientific ocean drilling to contribute even more important findings to the field of slow earthquakes, as results emerge from the recently completed Hikurangi subduction zone drilling during IODP Expeditions 372 and 375.

LONG-TERM BOREHOLE OBSERVATORIES: DETECTION AND CHARACTERIZATION OF SHALLOW SSES IN THE NEAR FIELD

Borehole monitoring systems at IODP drill sites offshore have provided some of the most robust observations to date of crustal strain during shallow subduction zone SSEs and associated hydrologic phenomena. These observatories involve a variety of configurations designed to monitor pore fluid pressure, temperature, strain, and tilt in the borehole rock formations, and to collect time series of formation fluids and flow rates using osmotically driven pumps (or so-called osmosamplers; e.g., Jannasch et al., 2003). In particular, changes in pore fluid pressure recorded in these observatories provide a highly sensitive measure of volumetric strain (Wang, 2004; Araki et al., 2017) in offshore regions near a trench that involve slip as small as only a few centimeters and where other geodetic methods lack resolution to detect or locate SSEs. Results from these instruments, most notably in the near-trench region of the Nankai (Araki et al., 2017) and Costa Rican (Davis and Villinger, 2006; Solomon et al., 2009; Davis et al., 2015) subduction zones (Figure 1), have yielded detailed observations of slow slip events that provide new constraints on location, timing, size, relationship to tremor, and potential associated changes in fault hydrogeology.

As one of the primary objectives of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), IODP Expeditions 319, 332, and 365 installed borehole observatories at two sites located ~24 km and 35 km landward of the subduction trench (Figures 1b and 2a). Site C0010 was drilled into the megasplay, one of the major active thrust faults splaying from the plate boundary, approximately 24 km from the trench. The borehole intersects the fault at 407 meters below seafloor (mbsf); the hole was initially drilled in 2009, and temporary instrument systems were deployed to monitor temperature and pore fluid pressure within the borehole (Saffer et al., 2010; Kopf et al., 2011). In 2016, a permanent observatory was installed that includes pore pressure sensors, a tiltmeter, an accelerometer, a broadband seismometer, and a volumetric strainmeter (Saffer et al., 2017). In addition, Site C0002 was drilled in the Kumano forearc basin (Figure 2a), about 11 km landward of Site C0010. A permanent observatory with the same configuration as that at Site C0010 was installed here in 2012. Together, the observatories provide a multiyear time series of formation pore pressure at two locations that define a "miniature array" with an ~11 km aperture. Formation fluid pressure changes serve as a sensitive proxy for volumetric strain during transient slow slip events, with the ability to resolve signals as small as ~10–20 nanostrain, equivalent to a crustal volume strain of approximately 10–20 parts per billion (Wang, 2004; Davis et al., 2009; Araki et al., 2017).

Since the 2012 installation of the observatory by IODP, the 5.3-year pressure time series reveal eight "strain events" that recur quasi-regularly at ~8–15 month intervals and with durations of a few days to several weeks (Figure 2b; Araki et al., 2017). These strain events are synchronous at the two boreholes, and some (though not all) are accompanied by swarms of low frequency tremors in a 40 km region of the forearc closest to the trench (Figure 1b) as detected by Japan's DONET (Dense Oceanfloor Network System) cabled seafloor network of seismometers (Kaneda et al., 2015). Similar low frequency earthquakes were observed previously in this region using shore-based networks (Ito and Obara, 2006). The sets of synchronous strain signals fall into three categories: (1) dilatation (extension) at both sites, (2) mixed signals with compression at Site C0010 and dilatation at Site C0002, and (3) compression at both sites. The magnitudes of these signals are best explained as slips of ~1–4 cm on the plate interface beneath the drill sites (Figure 2b), occurring over a period of days for the shortest events, to weeks for the longest. The sign of the strain signal allows delineation of the slipping regions, and suggests that most of the events are centered either landward, between the two boreholes (located ~30 km from the trench), or seaward of both sites, with slip possibly extending all the way to the trench.

These observations, enabled by offshore borehole observatories installed as part of IODP drilling, also indicate that repeating SSEs occur at shallow depths along the Nankai margin updip of the locked seismogenic zone and possibly extend to the trench. A third observatory, recently installed in the accretionary prism within 2 km of the trench axis during IODP Expedition 380, will provide key constraints on the seaward (trenchward) extent of slip in these SSEs (Kinoshita et al., 2018). The amount of slip deduced from the observatory signals suggests that SSEs accommodate ~30%–50% of the total amount of plate convergence, broadly consistent with partial seismic coupling (on order of 50%) in this area, as reported on the basis of a regional offshore GPS-A network (Yokota et al., 2016). This finding is especially noteworthy because the SSEs occur at a margin characterized by repeating great (M_w ~8) earthquakes that are thought to rupture at or close to seafloor depths (Satake, 1993; Sakaguchi et al., 2011), in a place where slow slip events were not necessarily expected.

Along the Costa Rican subduction margin, two borehole observatories were installed in 2002 during Ocean Drilling Program (ODP) Leg 205, offshore the Nicoya Peninsula in Costa Rica (Morris et al., 2003; Davis and Villinger, 2006; Figure 1d). One of the observatories (in Hole 1253A) was installed in the subducting Cocos Plate (~175 m seaward of the trench), penetrating the subducting sediments and underlying basement to ~600 mbsf. The second observatory (in Hole 1255A) penetrated the subduction thrust ~500 m landward of the trench at a depth of ~144 mbsf, to a total depth of 153 mbsf. Both observatories involve formation pore pressure monitoring, as well as geochemical fluid sampling and flow rate monitoring capabilities, using osmosamplers and osmoflowmeters (Jannasch et al., 2003; Solomon et al., 2009). These observatories were originally intended to assess the influence of the igneous basement on fluid flow, as well as to quantify the fluid pressure state on the plate boundary thrust

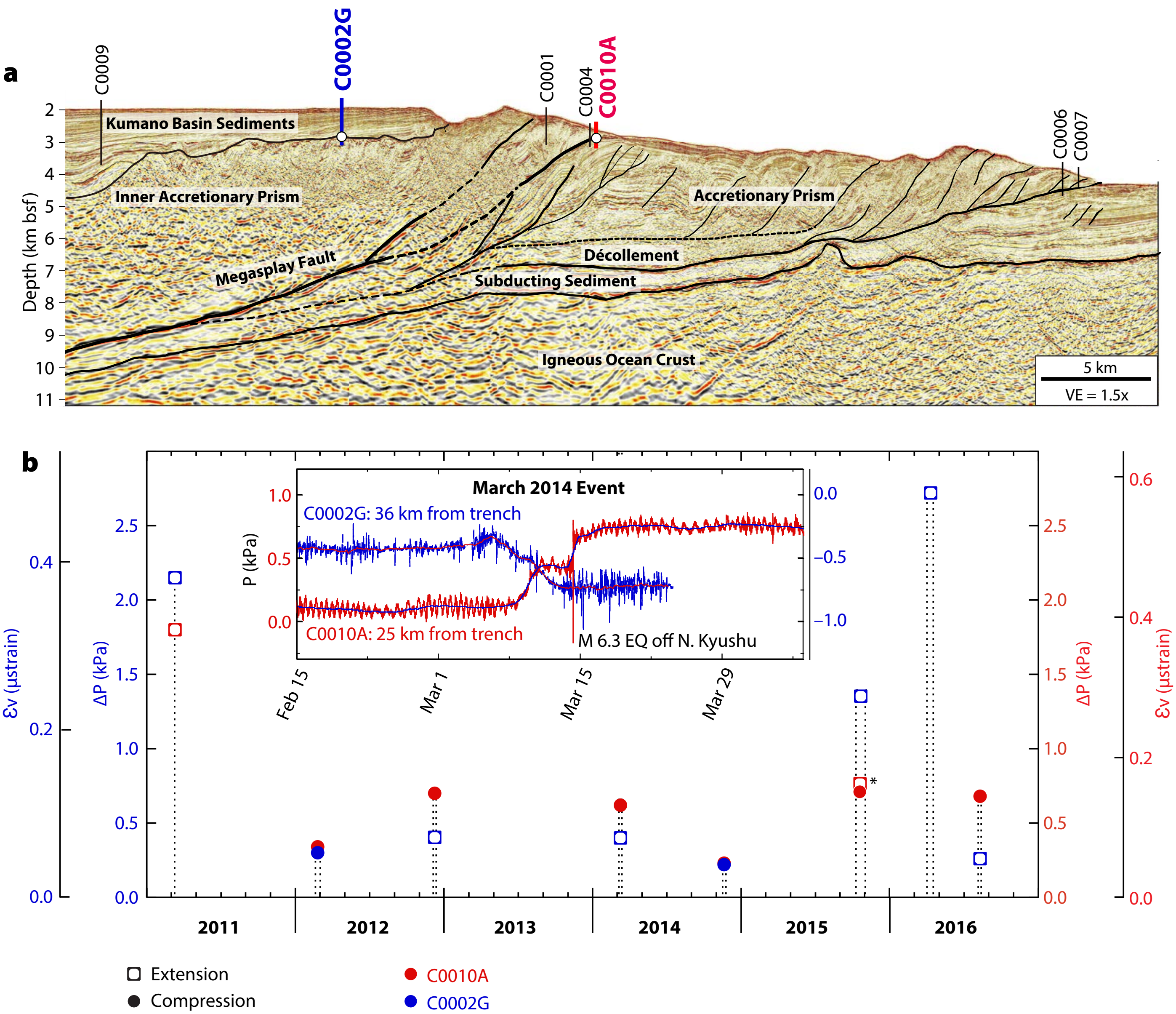


FIGURE 2. (a) Seismic line showing the locations of several Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) drill sites. Open white circles show the depths of pore pressure monitoring intervals at observatory boreholes C0002G (931–980 m) and C0010A (389-407 m). (b) Summary of SSE recurrence, shown by pressure and strain transients at Holes C0002G (blue) and C0010A (red). Dashed vertical lines indicate the duration of each event. A mixture of pressure increases (compressional strain; solid circles) and decreases (dilatational strain; open squares) are observed, and the sign of the strain provides constraints on the location of the slipping region in each event (after Araki et al., 2017). The Oct. 2015 event (denoted by asterisk) exhibited extension only at Hole C0002G, and initial compression followed by dilatation at Hole C0010A. The inset shows formation pore pressure records with oceanographic signals removed for an example SSE in March 2014. The thin line shows smoothed data using a 12 hr window.

and within the hanging wall of the fault system. However, they were also fortuitously located in a region of shallow slow slip events offshore the Nicoya Peninsula, as detected by a shore-based continuous GPS network (Dixon et al., 2014).

There is now mounting evidence for transient changes in pore pressure, and though less clear, accompanying shifts in fluid geochemistry and flow rates within the Costa Rica observatories that coincide with SSEs detected by onshore GPS sites. Solomon et al. (2009) identified two changes in fluid flow rates and fluid geochemistry (e.g., in the measured $^{87}Sr/^{86}Sr$ isotope ratios) that coincide with pore pressure shifts, which in turn are consistent with deformation due to a migrating slow slip event. This was the first evidence from an IODP borehole observatory that slow slip events impact hydrological processes and fluid geochemistry on the shallow subduction interface. Additional pore pressure transients have been observed following geodetically detected SSEs, which are interpreted as a delayed updip migration of SSEs to the trench (Davis et al., 2015). For example, in the weeks following a geodetically detected SSE in 2007, the observed pore pressure increases at Hole 1255A, combined with a pore pressure decrease at Hole 1253A as well as 1.4 cm of uplift suggested from the wellhead pressure data at Hole 1255A, led Davis et al. (2015) to suggest that the 2007 SSE involved up to 11 cm of slip to the trench.

DRILLING TO SAMPLE SSE FAULTS: FAULT ROCK PROPERTIES AND IN SITU CONDITIONS

Fault Friction and Effective Stress States: A Framework to Understand Unstable Slip and SSEs

Laboratory-based shearing experiments that simulate fault slip are one common approach to characterizing the strength and slip behavior of fault zones. In particular, rate-and-state friction—a theory that describes variations in frictional strength as functions of driving velocity (rate) and time (state)—provides a widely used and valuable theoretical framework for understanding fault sliding stability as it relates to earthquake nucleation and propagation, as well as other phenomena including fault healing, afterslip, and aseismic creep (e.g., Dieterich, 1979, 1981; Ruina, 1983; Marone, 1998). In the context of this theory, an increase in fault strength (or its resistance to sliding) as slip speed increases is known as velocity-strengthening behavior. Faults with this property are expected to slip aseismically, manifested as creep or earthquake afterslip. In contrast, velocity-weakening behavior, in which friction or resistance to sliding decreases with increasing sliding velocity, is a prerequisite for the nucleation of unstable, rapid slip that results in earthquakes (e.g., Marone, 1998; Scholz, 2002). Slow slip events are thought to occur where rock frictional properties are "conditionally stable," or near the transition from velocity-weakening to velocity-strengthening behavior. Although some previous laboratory studies have provided important insights that apply to slow slip phenomena, detailed investigations of natural material from major fault zones, particularly those that host slow slip, remain rare, and in situ sampling of these active faults generally requires drilling.

Although seismic fault slip requires velocity-weakening friction, the degree of instability also depends on other factors such as effective stress on the fault and elastic response properties of the surrounding fault rocks (e.g., Dieterich, 1986; Scholz, 1998). Under certain conditions, for example, if the rock frictional properties straddle the transition between velocity-weakening and velocity-strengthening behavior, faults may be quasi-unstable and exhibit oscillatory or slow failure (e.g., Baumberger et al., 1999; Leeman et al., 2016), such as observed during slow slip events. Another condition by which faults may exhibit transitional stability is low effective normal stress acting across the fault, either as a result of small total stresses related to shallow burial depth, or due to the presence of high pore fluid pressure (e.g., Scholz, 1998; Saffer and Tobin, 2011).

On the basis of these ideas, prevailing hypotheses for the occurrence of emergent slow slip events have focused on the roles of low effective stress, mediated by elevated pore fluid pressure, and/or frictional properties near the transition from velocity weakening to velocity strengthening (e.g., Kodaira et al., 2004; Saffer and Wallace, 2015). These ideas have been demonstrated in numerical models (Liu and Rice, 2007) and

> "In total, the powerful combination of these borehole observatories and IODP drilling, logging, and sampling of fault zones—where slow slip may occur—enables us to draw connections between fault slip behavior and fault architecture, frictional behavior, lithology, fluid composition, and physical properties."

laboratory experiments (Leeman et al., 2016; Scuderi et al., 2016), and are consistent with the inferred presence of elevated in situ pore pressure in SSE and slow earthquake source regions (e.g., Song et al., 2009; Kitajima and Saffer, 2012). The testing of natural samples is a key for experimental studies of friction targeting slow slip, because they preserve in situ composition and rock properties. IODP drilling has provided unique access to these materials from within shallow fault zones implicated in SSEs at several margins (e.g., Nankai, Costa Rica), as well as sediments on the incoming (subducting) plate that comprise the protolith for SSE fault zones at depth (e.g., Sumatra, Hikurangi). Samples and geophysical logs obtained via IODP drilling have also enabled a range of deformation experiments that allow estimation of in situ pore fluid pressure, porosity, and stress state at the drill sites and by inference within the surrounding volume of the crust (e.g., Tobin and Saffer, 2009; Kitajima and Saffer, 2012).

Insights from Experimental Studies on IODP Drill Cores

Friction Studies

In the Nankai Trough, SSEs, low frequency earthquakes (LFE), and very low frequency earthquakes (VLFEs) occur within the accretionary prism at shallow depths, likely on splay faults (e.g., Ito and Obara, 2006; Obana and Kodiara, 2009) and on the plate boundary thrust (Sugioka et al., 2012; Araki et al., 2017). Laboratory friction experiments have been conducted on samples recovered by ODP and IODP drilling across three major fault zones: (1) a major out-of-sequence splay fault (the megasplay; IODP Site C0004), (2) the frontal thrust zone near the trench (Site C0007) along the NanTroSEIZE transect (Figure 2a), and (3) the décollement zone near the trench (ODP Site 1174) on the Muroto transect ~200 km to the southwest (Shipboard Scientific Party, 2001). These results primarily document velocity-strengthening friction but also show that the degree of velocity-strengthening vs. velocity-weakening behavior can vary with sliding velocity (Ikari et al., 2009; Ikari and Saffer, 2011; Figure 3). Examples where frictional parameters straddle the velocity-strengthening/velocity-weakening transition occur consistently around slip velocities (~1 μm s^{-1}) similar to those of very low frequency earthquakes in the Nankai accretionary prism (Ito and Obara, 2006; Saffer and Wallace, 2015). Furthermore, data from samples at Sites C0004 and 1174 reveal that weakening due to accumulating slip could be an additional mechanism promoting the generation of low-velocity instabilities (Figure 3; Ikari et al., 2013).

In regions where fault zones have not been sampled, scientific ocean drilling still provides critical information on fault slip behavior through access to sediments on the incoming plate. These "subduction inputs" eventually host or line the plate interface, and laboratory testing of these sediments reveals they have characteristics relevant to the shallow plate boundary (e.g. Underwood, 2007; Hüpers et al., 2017; Ikari et al., 2018). An example is the Hikurangi margin offshore New Zealand, where geodetic observations provide a robust record of repeating slow slip events (Wallace et al., 2012, 2016; Wallace and Beavan, 2010). Laboratory experiments have been conducted on a sample of carbonate-rich sediment collected at ODP Site 1124, located seaward of the deformation front, that is expected to host the plate boundary (Rabinowitz et al., 2018). These experiments document a gradual shift from velocity-weakening to velocity-strengthening friction as a function of sliding velocity, with the transition occurring at <1 μm s^{-1}, which is broadly similar to slip rates of SSEs at the Hikurangi margin determined from geodetic studies.

The variation in frictional behavior with sliding velocity observed in experiments on very fine-grained natural fault zone materials, so-called fault gouges, incoming sediments to subduction zones, and synthetic clay-rich fault gouges (e.g., Ikari et al., 2009; Saito et al., 2013; Saffer and Wallace, 2015) highlights the

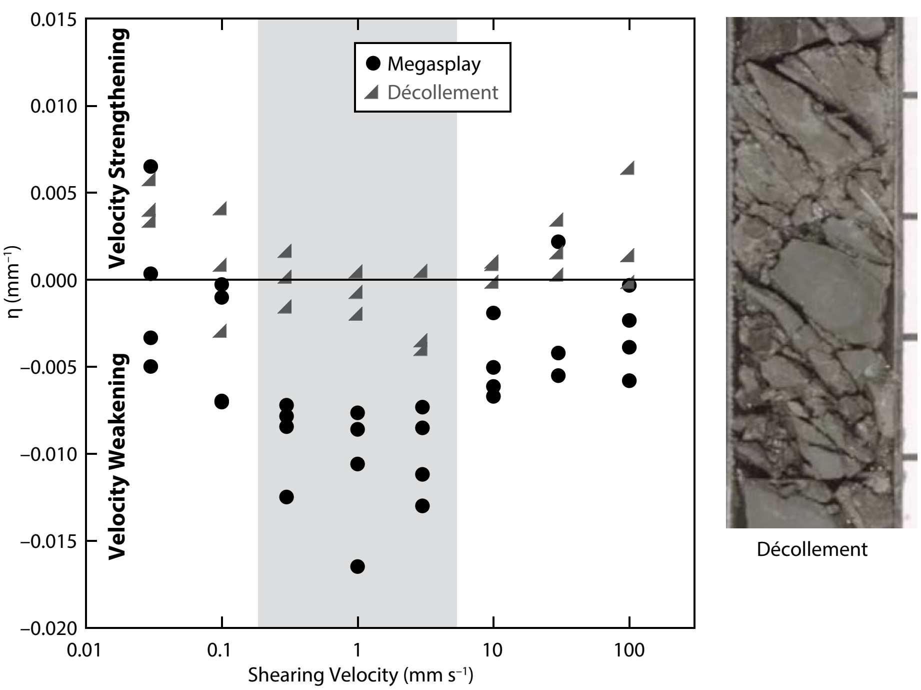


FIGURE 3. (left) Results of laboratory friction tests on core samples from the Nankai Trough megasplay and décollement zones showing slip-dependence of friction *η* as a function of shearing velocity (from Ikari et al., 2013). (right) The photo shows an example of a core sample from the décollement fault zone collected during ODP Leg 190 from Site 1174B, core section 72R-2. Tick marks on photo indicate 5 cm spacing.

importance of characterizing frictional behavior across a wide range of slip rates. The behavior of natural fault materials at very low sliding velocities, spanning slip rates from plate tectonic to slow earthquake to SSE, has emerged as particularly important to understanding the nucleation and generation of SSEs. A suite of experiments was recently conducted on fault zone samples at slip rates much lower than those typically explored in experimental rate-and-state friction studies but comparable to plate convergence rates of a few centimeters per year. The first of these "slow" experiments was performed on a sample from the shallow plate boundary fault zone within the region of the 2011 Tōhoku-oki earthquake where the coseismic slip was >50 m; this sample was recovered from IODP Site C0019 during the Japan Trench Fast Drilling Project (JFAST; Chester et al., 2013). These experiments revealed that when driven at plate tectonic motion rates, the fault samples exhibited velocity-weakening friction, generating laboratory SSEs characterized by strength perturbations with stress drops and peak slip velocities similar to those observed geodetically during the actual Tōhoku-oki earthquake (Ikari et al., 2015; Figure 4). Tests on IODP drill core samples from other subduction zones where shallow SSEs are known to occur, such as the Nankai Trough, Japan Trench, and Costa Rica, yield similar results (Ikari and Kopf, 2017).

The identification of frictional behavior conducive to shallow slow slip also carries important implications for earthquake hazards. If slow slip reflects the potential for velocity-weakening (and thus seismic) behavior, these regions could also be susceptible to shallow coseismic slip or tsunami earthquakes, depending on different loading conditions. Therefore, compared to purely creeping fault conditions, these regions may be at greater risk than previously thought (e.g., Polet and Kanamori, 2000; Lay and Kanamori, 2011). Thus far, laboratory experiments on natural fault zone samples collected via IODP drilling have provided important insights into the mechanisms of slow fault slip in several active subduction zones. Continued refinement of our understanding of shallow fault slip and characterizations of other regions will depend critically on the continued recovery of core material by scientific ocean drilling.

Constraints on Fluid and Stress States

An additional key to understanding the origin of transient slow slip events requires quantification of in situ effective stress states and pore fluid pressures within SSE source regions. The shallow portion of the Nankai Trough, where low frequency earthquakes and SSEs occur (Ito and Obara, 2006; Sugioka et al., 2012; Araki et al., 2017), coincides with low seismic velocity zones revealed in seismic reflection and refraction studies (Park et al., 2010; Kamei et al., 2012). Kitajima and Saffer (2012) conducted deformation

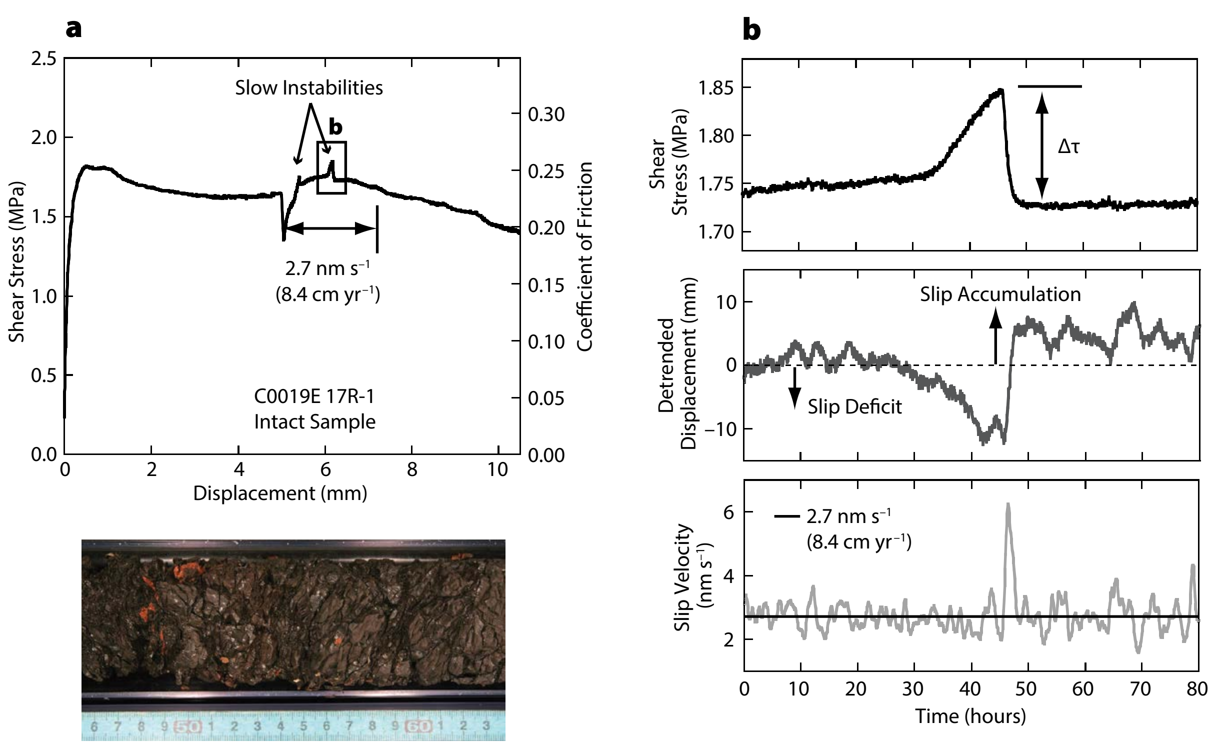


FIGURE 4. Results of laboratory friction tests on a sample of the Japan Trench plate-boundary fault zone. (a) Frictional strength as a function of displacement showing the portion of the test conducted at the plate convergence rate. Note the two perturbations, the second of which is shown in more detail in (b). (b) Shear stress, detrended slip displacement, and sample slip velocity during the second slip instability as a function of time. Slip deficit accumulates during the loading phase, and during the stress drop, slip rapidly re-accumulates and the slip velocity more than doubles, but remains slow. The photo shows an example of a core sample from the fault zone collected during IODP Expedition 343 from Site C0019E, core section 17R-1. Scale is in cm.

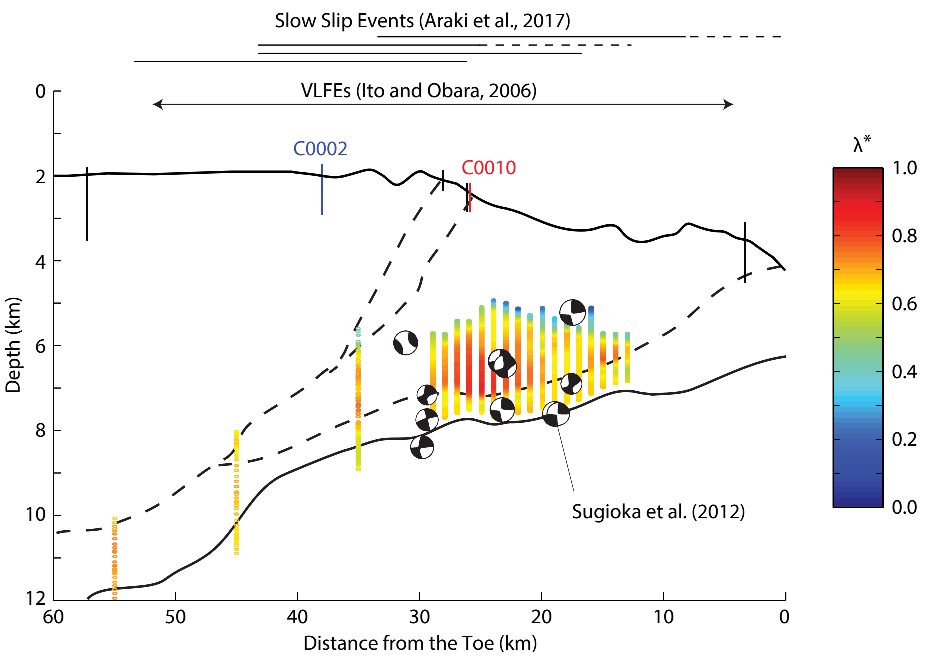


FIGURE 5. Pore pressure ratio, λ*, in the low seismic velocity zone observed along the IODP NanTroSEIZE Kumano transect at the Nankai Trough (Figure 2; Kitajima and Saffer, 2012). λ* is the ratio of excess pore pressure to effective overburden stress at hydrostatic pressure; λ* ranges 0 (hydrostatic pore pressure) and 1 (lithostatic pore pressure). The beach balls represent moment tensor solutions for low frequency earthquakes reported by Sugioka et al. (2012). The regions of observed low frequency earthquakes (Ito and Obara, 2006) and slow slip events (Araki et al., 2017) are also shown on top.

experiments on IODP cores recovered during the NanTroSEIZE project to constrain relations between P-wave velocity, porosity, and effective mean stress under simulated tectonic loading conditions. Combined with P-wave velocity values from seismic reflection and refraction data, their analysis reveals that pore pressure exceeds 90% of lithostatic pressure in the region of low Vp and is coincident with the locations of observed VLFEs and SSEs (Figure 5). The elevated pore pressure is interpreted to result from enhanced mechanical loading by lateral tectonic stresses in the wider subduction zone area. The integration of core and seismic data to estimate pore pressure in the near-trench region at the Nankai Trough is arguably the most robust inference of pore fluid pressure available for a region where slow slip and tremor occur.

Other studies have also focused on quantifying in situ stress and pore pressure in shallow subduction zones by integrating laboratory deformation experiments on IODP cores, seismic reflection surveys, drilling and logging data, and numerical modeling (Spinelli et al., 2006; Tobin and Saffer, 2009; Huffman et al., 2016; Brodsky et al., 2017; Han et al., 2017; Li et al., 2018). Elevated pore pressure has been estimated from seismic reflection and drilling data within the underthrust sediments in regions that are ~20 km from the trenches along the Muroto transect of the Nankai Trough (Tobin and Saffer, 2009), the Central Aleutian margin (Li et al., 2018), and the Cascadia margin (Han et al., 2017). Hydrologic models that simulate fluid production and flow based on IODP drilling data and laboratory measurements on core samples also suggest that pore pressure at the Costa Rica subduction zone is nearly lithostatic (as a function of the rock overburden) beneath the shallow plate interface where SSEs may propagate to the trench, whereas it is hydrostatic (with fluid pressures at equilibrium at depth) to slightly overpressured in the overriding plate (Spinelli et al., 2006). Detailed analyses of borehole stress indicators combined with rock strength data on core samples further reveals that the in situ stress state may vary spatially and temporally and that differential stresses in the near field of the near-trench region of the subduction thrust may be very low, suggesting that shallow SSE source regions are sites of high pore pressure, low effective stresses, and low strength (e.g., Huffman and Saffer, 2016; Brodsky et al., 2017). Inferences of fluid pressure conditions and stress states from drilling and seismic data, laboratory experiments, and modeling studies require increased integration with seismological and geodetic observations of SSEs, tremor, and low frequency earthquakes to even further advance our understanding of transient slow slip phenomena.

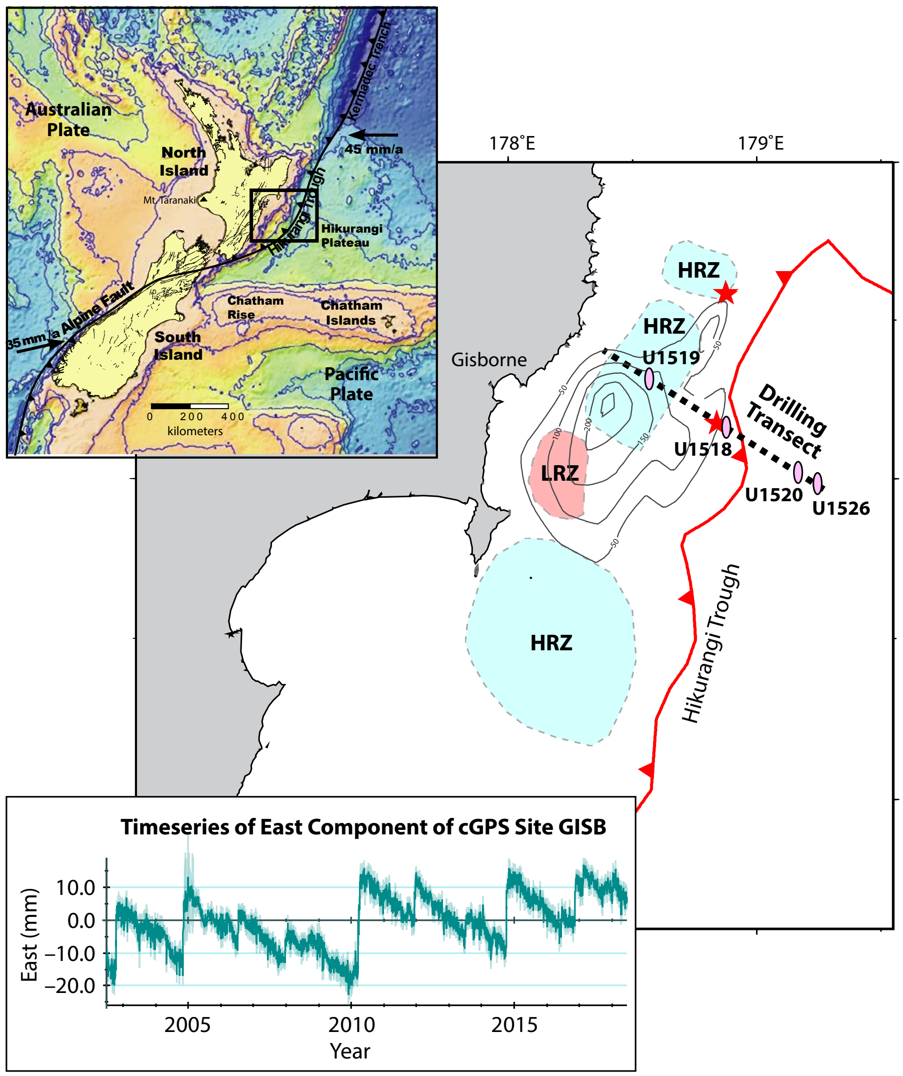
IODP DRILLING FOCUSED ON SHALLOW SSES AT THE HIKURANGI SUBDUCTION ZONE, NEW ZEALAND

Slow slip events at the northern Hikurangi subduction margin, New Zealand, are among the best-documented shallow SSEs on Earth. The regularity and well-characterized short repeat interval (one to two years) of the Hikurangi SSEs (Wallace and Beavan, 2010; Wallace et al., 2012) allow monitoring over multiple SSE cycles, with the potential to document the spatial and temporal distribution of strain accumulation and release in the very-near field of the SSEs, as well as any associated hydrogeologic phenomena. The close proximity of the seafloor to the north Hikurangi SSEs (< 2–15 km; Wallace et al., 2016; Figure 6) enables sampling of rocks that are eventually transported downdip to the known SSE source region, revealing the rock properties, composition, and lithologic and structural character of material that hosts slow slip.

IODP Expeditions 372 (Pecher et al., 2018) and 375 (Saffer et al., 2018) were mounted to investigate SSEs at northern Hikurangi, and together constitute the first-ever scientific drilling effort undertaken specifically to target transient slow slip behavior. The processes and in situ conditions that underlie subduction zone SSEs were examined by coring and logging while drilling (LWD) through one of the main active faults near the deformation front (Site U1518), the upper plate overlying the region of large slow slip (Site U1519), and the incoming sedimentary succession and igneous basement (Sites U1520 and U1526) (Figures 6 and 7). Expedition 375 also undertook installation of borehole observatories within the active fault (U1518) and upper plate (U1519). Together, the coring, logging, and observatory data will test a suite of hypotheses about the fundamental mechanics and behavior of slow slip events and their relationship to potentially damaging earthquakes along the subduction interface.

The scientific objectives of the Hikurangi IODP drilling programs are three-fold: (1) to document the physical, hydrogeological, and chemical properties, lithology, geometry, microstructure, and thermal state of one of the most active faults near the trench, as well as the inputs of sediment and upper igneous crust of the subducting Pacific Plate, with an emphasis on intervals that host, or will eventually host, SSEs; (2) to characterize the stress regime, thermal structure, porosity, permeability, lithology, pore fluid pressure state, fluid chemistry, flow pathways, and structural geology of the upper plate overlying the SSE source region; and (3) to install observatories in the upper plate and an active out-of-sequence thrust that span the SSE source region, in order to monitor volumetric strain (using pore pressure as a proxy) and the evolution of physical, hydrological, and chemical properties throughout the SSE cycle.

These objectives are designed to address key questions regarding the generation of slow slip and the mechanics of subduction megathrusts. In particular, an overarching working hypothesis to be tested by the data and samples acquired at the Hikurangi margin is that slow earthquakes occur in regions containing highly overpressurized fluids, under low effective normal stress, and on faults with transitional frictional behavior characterized by geometric and compositional heterogeneities. Data and samples from the Hikurangi margin will also enable evaluation of the role that temperature and metamorphism may play in these processes. The observatories, which will be in place for multiple SSE cycles, will reveal the influence of slow slip events on fluid flow and deformation within the fault zone and upper plate. Downhole pore pressure sensing in both observatories (at U1518 and U1519; Figure 7) will provide a sensitive proxy for volumetric strain, and will help resolve the detailed spatiotemporal evolution of shallow slow slip, as well as much smaller SSEs than is currently possible using conventional surface-based geodetic techniques (e.g., Araki et al., 2017).



HRZ: Zones of high amplitude reflectivity above the plate interface that is interpreted as fluid-rich subducted sediment

LRZ: Lens of low amplitude material between an upper and lower high-amplitude reflector with complex 3D geometry lies on or below the interface

FIGURE 6. Tectonic setting (upper left inset) and location of slip on the interface in September/October 2014 captured by a seafloor network of absolute pressure gauges (black contours, labeled in 50 mm increments; Wallace et al., 2016) and the reflective properties of the subduction interface (Bell et al., 2010) at northern Hikurangi. Black dashed line shows the location of the drilling transect (see Figure 7); pink ellipses are IODP Expedition 372 and 375 drill sites. Red stars indicate the locations of two tsunamigenic subduction interface earthquakes (M_w 6.9–7.1) that occurred in March and May of 1947. The lower left inset shows the east component of the position time series for a cGPS site near Gisborne to demonstrate the repeatability of SSEs since they were first observed in 2002.

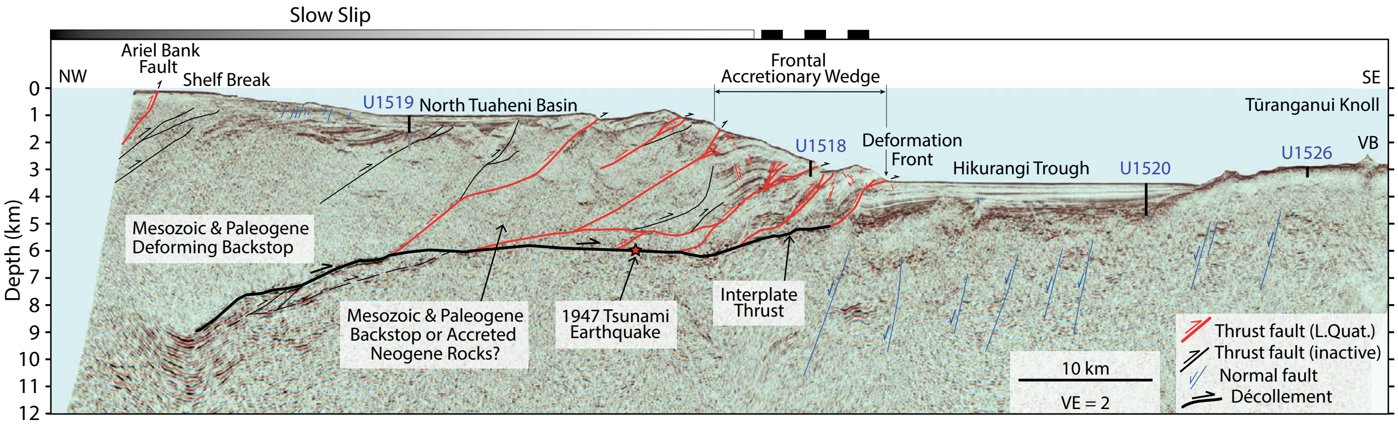


FIGURE 7. Depth-converted seismic Profile 05CM-04 from the Hikurangi margin drilling transect showing locations of the sites that were drilled during IODP Expeditions 372 and 375, as well as structural interpretation. Star = projected location of March 1947 tsunami earthquake. The location of the profile coincides with the drilling transect shown in Figure 6. VB = volcanic cone. VE = vertical exaggeration. Seismic profile and interpretations from Barker et al. (2018).

SUMMARY

The data and samples gathered during several recent IODP expeditions to study slow slip events in subduction zone megathrust settings have been and remain the subject of wide-ranging post-expedition research efforts. Data from borehole seismic observatories offshore Japan and Costa Rica are retrieved regularly, and in the case of the NanTroSEIZE observatories, are transmitted in real time via the DONET cabled network. The first data from similar CORK (sealed borehole) observatories offshore New Zealand at the northern Hikurangi subduction margin will be retrieved within the next few years.

In total, the powerful combination of these borehole observatories and IODP drilling, logging, and sampling of fault zones—where slow slip may occur—enables us to draw connections between fault slip behavior and fault architecture, frictional behavior, lithology, fluid composition, and physical properties. Over the coming years, the results from past and future scientific ocean drilling expeditions that target shallow slow slip events will produce an important step-change in our understanding of slow slip processes and the mechanics of subduction megathrusts.

REFERENCES

Araki, E., D.M. Saffer, A. Kopf, L.M. Wallace, T. Kimura, Y. Machida, and S. Ide. 2017. Recurring and triggered slow slip events near the trench at the Nankai Trough subduction megathrust. *Science* 356:1,157–1,160, https://doi.org/10.1126/science.aan3120.

Audet, P., M.G. Bostock, N.I. Christensen, and S.M. Peacock. 2009. Seismic evidence for overpressured subducted oceanic crust and megathrust fault sealing. *Nature* 457(7225):76–78, https://doi.org/10.1038/nature07650.

Barker, D.H.N., S. Henrys, F.C. Tontini, P.M. Barnes, D. Bassett, E. Todd, and L.M. Wallace. 2018. Geophysical constraints on the relationship between seamount subduction, slow slip and tremor at the north Hikurangi subduction zone, New Zealand. *Geophysical Research Letters* 45(23):12,804–12,813, https://doi.org/10.1029/2018GL080259.

Baumberger, T., P. Berthoud, and C. Caroli. 1999. Physical analysis of the state- and rate-dependent friction law: Part II. Dynamic friction. *Physical Review B* 60(6):3,928–3,939, https://doi.org/10.1103/PhysRevB.60.3928.

Bell, R., R. Sutherland, D.H.N. Barker, S. Henrys, S. Bannister, L. Wallace, and J. Beavan. 2010. Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events. *Geophysical Journal International* 180(1):34–48, https://doi.org/10.1111/j.1365-246X.2009.04401.x.

Brodsky, E.E., D. Saffer, P. Fulton, F. Chester, M. Conin, K. Huffman, J.C. Moore, and H.Y. Wu. 2017. The postearthquake stress state on the Tōhoku megathrust as constrained by reanalysis of the JFAST breakout data. *Geophysical Research Letters* 44(16):8,294–8,302, https://doi.org/10.1002/2017GL074027.

Brown, K.M., M.D. Tryon, H.R. DeShon, L.M. Dorman, and S.Y. Schwartz. 2005. Correlated transient fluid pulsing and seismic tremor in the Costa Rica subduction zone. *Earth and Planetary Science Letters* 238:189–203, https://doi.org/10.1016/j.epsl.2005.06.055.

Bürgmann, R. 2018. The geophysics, geology and mechanics of slow fault slip. *Earth and Planetary Science Letters* 495:112–134, https://doi.org/10.1016/j.epsl.2018.04.062.

Chester, F.M., J.J. Mori, N. Eguchi, S. Toczko, and Expedition 343/343T Scientists. 2013. *Proceedings of the Integrated Ocean Drilling Program*, vol. 343/343T. Integrated Ocean Drilling Program Management International Inc., Tokyo, http://publications.iodp.org/proceedings/343_343T/343title.htm.

Davis, E.E., and H.W. Villinger. 2006. Transient formation fluid pressures and temperatures in the Costa Rica forearc prism and subducting oceanic basement: CORK monitoring at ODP Sites 1253 and 1255. *Earth and Planetary Science Letters* 245:232–244, https://doi.org/10.1016/j.epsl.2006.02.042.

Davis, E.E., K. Wang, K. Becker, and M. Kinoshita. 2009. Co-seismic and post-seismic pore-fluid pressure changes in the Philippine Sea plate and Nankai decollement in response to a seismogenic strain event off Kii Peninsula, Japan. *Earth, Planets, Space* 61:649–657, https://doi.org/10.1186/BF03353174.

Davis, E.E., H. Villinger, and T. Sun. 2015. Slow and delayed deformation and uplift of the outermost subduction prism following ETS and seismogenic slip events beneath Nicoya Peninsula, Costa Rica. *Earth and Planetary Science Letters* 410:117–127, https://doi.org/10.1016/j.epsl.2014.11.015.

Dieterich, J.H. 1979. Modeling of rock friction: Part 1. Experimental results and constitutive equations. *Journal of Geophysical Research* 84(B5):2,161–2,168, https://doi.org/10.1029/JB084iB05p02161.

Dieterich, J.H. 1981. Constitutive properties of faults with simulated gouge. Pp. 102–120 in *Mechanical Behavior of Crustal Rocks: The Handin Volume*. N.L. Carter, M. Friedman, J.M. Logan, and D.W. Stearns, eds, Geophysical Monograph Series vol. 24, American Geophysical Union, Washington, DC, https://doi.org/10.1029/GM024p0103.

Dieterich, J.H. 1986. A model for the nucleation of earthquake slip. Pp. 37–47 in *Earthquake Source Mechanics*. S. Das, J. Boatwright, and C.H. Scholz, eds, Geophysical Monograph Series, vol. 37, American Geophysical Union, Washington, DC, https://doi.org/10.1029/GM037p0037.

Dixon, T.H., Y. Jiang, R. Malservisi, R. McCaffrey, N. Voss, M. Protti, and V. Gonzalez. 2014. Earthquake and tsunami forecasts: Relation of slow slip events to subsequent earthquake rupture. *Proceedings of the National Academy of Sciences of the United States of America* 111(48):17,039–17,044, https://doi.org/10.1073/pnas.1412299111.

Douglas, A., J. Beavan, L. Wallace, and J. Townend. 2005. Slow slip on the northern Hikurangi subduction interface, New Zealand. *Geophysical Research Letters* 32, L16305, https://doi.org/10.1029/2005GL023607.

Dragert, H., K. Wang, and T.S. James. 2001. A silent slip event on the deeper Cascadia subduction interface. *Science* 292:1,526–1,528, https://doi.org/10.1126/science.1060152.

Goulty, N.R., and R. Gilman. 1978. Repeated creep events on the San Andreas Fault near Parkfield, California, recorded by a strainmeter array. *Journal of Geophysical Research* 83(B11):5,415–5,419, https://doi.org/10.1029/JB083iB11p05415.

Han, S., N.L. Bangs, S.M. Carbotte, D.M. Saffer, and J.C. Gibson. 2017. Links between sediment consolidation and Cascadia megathrust slip behaviour. *Nature Geoscience* 10:954–959, https://doi.org/10.1038/s41561-017-0007-2.

Hirose, H.K. Hirahara, F. Kimata, N. Fujii, and S. Miyazaki. 1999. A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan. *Geophysical Research Letters* 26(21):3,237–3,240, https://doi.org/10.1029/1999GL010999.

Hirose, H., and K. Obara. 2005. Repeating short- and long-term slow slip events with deep tremor activity around the Bungo channel region, southwest Japan. *Earth, Planets, and Space* 57:961–972, https://doi.org/10.1186/BF03351875.

Huffman, K.A., and D.M. Saffer. 2016. In situ stress magnitudes at the toe of the Nankai Trough Accretionary Prism, offshore Shikoku Island, Japan. *Journal of Geophysical Research* 121(2):1,202–1,217, https://doi.org/10.1002/2015JB012415.

Hüpers, A., M.E. Torres, S. Owari, L.C. McNeill, B. Dugan, T.J. Henstock, K.L. Milliken, K.E. Petronotis, J. Backman, S. Boulange, and others. 2017. Release of mineral-bound water prior to subduction tied to shallow seismogenic slip off Sumatra. *Science* 356:841–844, https://doi.org/10.1126/science.aal3429.

Ide, S., G.C. Beroza, D.R. Shelly, and T. Uchide. 2007. A scaling law for slow earthquakes. *Nature* 447:76–79, https://doi.org/10.1038/nature05780.

Ikari, M.J., D.M. Saffer, and C. Marone. 2009. Frictional and hydrologic properties of a major splay fault system, Nankai subduction zone. *Geophysical Research Letters* 36(20), L20313, https://doi.org/10.1029/2009GL040009.

Ikari, M.J., and D.M. Saffer. 2011. Comparison of frictional strength and velocity dependence between fault zones in the Nankai accretionary complex. *Geochemistry, Geophysics, Geosystems* 12, Q0AD11, https://doi.org/10.1029/2010GC003442.

Ikari, M.J., C. Marone, D.M. Saffer, and A.J. Kopf. 2013. Slip weakening as a mechanism for slow earthquakes. *Nature Geoscience* 6(6):468–472, https://doi.org/10.1038/ngeo1818.

Ikari, M.J., Y. Ito, K. Ujiie, and A.J. Kopf. 2015. Spectrum of slip behaviour in Tōhoku fault zone samples at plate tectonic slip speeds. *Nature Geoscience* 8:870–874, https://doi.org/10.1038/ngeo2547.

Ikari, M.J., and A.J. Kopf. 2017. Seismic potential of weak, near-surface faults revealed at plate tectonic slip rates. *Science Advances* 3:e1701269, https://doi.org/10.1126/sciadv.1701269.

Ikari, M.J., A.J. Kopf, A. Hüpers, and C. Vogt. 2018. Lithologic control of frictional strength variation in subduction zone sediment inputs. *Geosphere* 14(2):604–625, https://doi.org/10.1130/GES01546.1.

Ito, Y., and K. Obara. 2006. Very low frequency earthquakes within accretionary prisms are very low stress-drop earthquakes. *Geophysical Research Letters* 33, L09302, https://doi.org/10.1029/2006GL025883.

Ito, Y., K. Obara, K. Shiomi, S. Sekine, and H. Hirose. 2007. Slow earthquakes coincident with episodic tremors and slow slip events. *Science* 315(5811):503–506, https://doi.org/10.1126/science.1134454.

Ito, Y., R. Hino, M. Kido, H. Fujimoto, Y. Osada, D. Inazu, Y. Ohta, T. Iinuma, M. Ohzono, S. Miura, and others. 2013. Episodic slow slip events in the Japan subduction zone before the 2011 Tōhoku-oki earthquake. *Tectonophysics* 600:14–26, https://doi.org/10.1016/j.tecto.2012.08.022.

Jannasch, H.W., E.E. Davis, M. Kastner, J.D. Morris, T.L. Pettigrew, J.N. Plant, E.A. Solomon, H.W. Villinger, and C.G. Wheat. 2003. CORK-II: Long-term monitoring of fluid chemistry, fluxes, and hydrology in instrumented boreholes at the Costa Rica subduction zone. Pp. 1–36 in *Proceedings of the Ocean Drilling Program, Initial Reports,* vol. 205. J.D. Morris, H.W. Villinger, and A. Klaus, eds, College Station, TX, https://doi.org/10.2973/odp.proc.ir.205.102.2003.

Kamei, R., R.G. Pratt, and T. Tsuji. 2012. Waveform tomography imaging of a megasplay fault system in the seismogenic Nankai subduction zone. *Earth and Planetary Science Letters* 317–318:343–353, https://doi.org/10.1016/j.epsl.2011.10.042.

Kaneda, Y., K. Kawaguchi, E. Araki, H. Matsumoto, T. Nakamura, S. Kamiya, K. Ariyoshi, T. Hori, T. Baba, and N. Takahashi. 2015. Development and application of an advanced ocean floor network system for megathrust earthquakes and tsunamis. Pp. 643–662 in *Seafloor Observatories.* P. Favali, L. Beranzoli, and A. De Santis, eds, Springer Praxis Books, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-11374-1_25.

Kato, A., K. Obara, T. Igarashi, H. Tsuruoka, S. Nakagawa, and N. Hirata. 2012. Propagation of slow slip leading up to the M_w 9.0 Tōhoku-oki earthquake. *Science* 335:705–708, https://doi.org/10.1126/science.1215141.

Kinoshita, M., K. Becker, S. Toczko, and the Expedition 380 Scientists. 2018. *Expedition 380 Preliminary Report: NanTroSEIZE Stage 3: Frontal Thrust Long-Term Borehole Monitoring System (LTBMS).* International Ocean Discovery Program, College Station, TX, https://doi.org/10.14379/iodp.pr.380.2018.

Kitajima, H., and D.M. Saffer. 2012. Elevated pore pressure and anomalously low stress in regions of low frequency earthquakes along the Nankai Trough subduction megathrust. *Geophysical Research Letters* 39(23), L23301, https://doi.org/10.1029/2012GL053793.

Kodaira, S., T. Iidaka, A. Kato, J.-O. Park, T. Iwasaki, and Y. Kaneda. 2004. High pore fluid pressure may cause silent slip in the Nankai Trough. *Science* 304(5675):1,295–1,298, https://doi.org/10.1126/science.1096535.

Kopf, A., E. Araki, S. Toczko, and the Expedition 332 Scientists. 2011. *Proceedings of the Integrated Ocean Drilling Program, 332: NanTroSEIZE Stage 2: Riserless Observatory.* Integrated Ocean Drilling Program Management International Inc., Tokyo, Japan, https://doi.org/10.2204/iodp.proc.332.2011.

Kostoglodov, V., S.K. Singh, J.A. Santiago, S.I. Franco, K.M. Larson, A.R. Lowry, and R. Bilham. 2003. A large silent earthquake in the Guerrero seismic gap, Mexico. *Geophysical Research Letters* 30(15), https://doi.org/10.1029/2003GL017219.

Lay, T., and H. Kanamori. 2011. Insights from the great 2011 Japan earthquake. *Physics Today* 64(12):33–39, https://doi.org/10.1063/PT.3.1361.

Leeman, J.R., D.M. Saffer, M.M. Scuderi, and C. Marone. 2016. Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes. *Nature Communications* 7:11104, https://doi.org/10.1038/ncomms11104.

Li, J., D.J. Shillington, D.M. Saffer, A. Bécel, M.R. Nedimović, H. Kuehn, S.C. Webb, K.M. Keranen, and G.A. Abers. 2018. Connections between subducted sediment, pore-fluid pressure, and earthquake behavior along the Alaska megathrust. *Geology* 46(4):299–302, https://doi.org/10.1130/G39557.1.

Linde, A.T., M.T. Gladwin, M.J. Johnston, R.L. Gwyther, and R.G. Bilham. 1996. A slow earthquake sequence on the San Andreas Fault. *Nature* 383(6595):65–68, https://doi.org/10.1038/383065a0.

Liu, Y., and J.R. Rice. 2007. Spontaneous and triggered aseismic deformation transients in a subduction fault model. *Journal of Geophysical Research* 112(B9), B09404, https://doi.org/10.1029/2007JB004930.

Marone, C. 1998. Laboratory-derived friction laws and their application to seismic faulting. *Annual Review of Earth and Planetary Sciences* 26:643–696, https://doi.org/10.1146/annurev.earth.26.1.643.

Morris, J.D., H.W. Villinger, A. Klaus, D.M. Cardace, V.M.C. Chavagnac, P.D. Clift, M. Haeckel, T. Hisamitsu, M. Kastner, M. Pfender, and others. 2003. *Proceedings of the Ocean Drilling Program, Initial Reports,* 205. Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.205.2003.

Obana, K., and S. Kodaira. 2009. Low-frequency tremors associated with reverse faults in a shallow accretionary prism. *Earth and Planetary Science Letters* 287(1–2):168–174, https://doi.org/10.1016/j.epsl.2009.08.005.

Obara, K., 2002. Nonvolcanic deep tremor associated with subduction in southwest Japan. *Science* 296(5573):1,679–1,681, https://doi.org/10.1126/science.1070378.

Obara, K., H. Hirose, F. Yamamizu, and K. Kasahara. 2004. Episodic slow slip events accompanied by non-volcanic tremors in southwest Japan subduction zone. *Geophysical Research Letters* 31(23), L23602, https://doi.org/10.1029/2004GL020848.

Obara, K., and A. Kato. 2016. Connecting slow earthquakes to huge earthquakes. *Science* 353(6296):253–257, https://doi.org/10.1126/science.aaf1512.

Ohta, Y., J.T. Freymueller, S. Hreinsdóttir, and H. Suito. 2006. A large slow slip event and the depth of the seismogenic zone in the south central Alaska subduction zone. *Earth and Planetary Science Letters* 247(1–2):108–116, https://doi.org/10.1016/j.epsl.2006.05.013.

Outerbridge, K.C., T.H., Dixon, S.Y. Schwartz, J.I. Walter, M. Protti, V. Gonzalez, J. Biggs, M. Thorwart, and W. Rabbel. 2010. A tremor and slip event on the Cocos-Caribbean subduction zone as measured by a global positioning system (GPS) and seismic network on the Nicoya Peninsula, Costa Rica. *Journal of Geophysical Research* 115, B10408, https://doi.org/10.1029/2009JB006845.

Park, J.O., G. Fujie, L. Wijerathne, T. Hori, S. Kodaira, Y. Fukao, G.F. Moore, N.L. Bangs, S.I. Kuramoto, and A. Taira. 2010. A low-velocity zone with weak reflectivity along the Nankai subduction zone. *Geology* 38(3):283–286, https://doi.org/10.1130/G30205.1.

Pecher, I.A., P.M. Barnes. L.J. LeVay, and the Expedition 372 Scientists. 2018. *IODP Expedition 372 Preliminary Report: Creeping Gas Hydrate Slides and Hikurangi LWD*. International Ocean Discovery Program, https://doi.org/10.14379/iodp.pr.372.2018.

Peng, Z., and J. Gomberg. 2010. An integrated perspective of the continuum between earthquakes and slow-slip phenomena. *Nature Geoscience* 3(9):599–607, https://doi.org/10.1038/ngeo940.

Polet, J., and H. Kanamori. 2000. Shallow subduction zone earthquakes and their tsunamigenic potential. *Geophysical Journal International* 142:684–702, https://doi.org/10.1046/j.1365-246x.2000.00205.x.

Rabinowitz, H.S., H.M. Savage, R.M. Skarbek, M.J. Ikari, B.M. Carpenter, and C. Collettini. 2018. Frictional behavior of input sediments to the Hikurangi Trench, New Zealand. *Geochemistry, Geophysics, Geosystems* 19, https://doi.org/10.1029/2018GC007633.

Radiguet, M., F. Cotton, M. Vergnolle, M. Campillo, A. Walpersdorf, N. Cotte, and V. Kostoglodov. 2012. Slow slip events and strain accumulation in the Guerrero gap, Mexico. *Journal of Geophysical Research* 117, B04305, https://doi.org/10.1029/2011JB008801.

Rogers, G., and H. Dragert. 2003. Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip. *Science* 300(5627):1,942–1,943, https://doi.org/10.1126/science.1084783.

Ruina, A. 1983. Slip instability and state variable friction laws. *Journal of Geophysical Research* 88(B12):10,359–10,370, https://doi.org/10.1029/JB088iB12p10359.

Ruiz, S., M. Metois, A. Fuenzalida, J. Ruiz, F. Leyton, R. Grandin, C. Vigny, R. Madariaga, and J. Campos. 2014. Intense foreshocks and a slow slip event preceded the 2014 Iquique M_w 8.1 earthquake. *Science* 345:1,165–1,169, https://doi.org/10.1126/science.1256074.

Sacks, I.S., S. Suyehiro, A.T. Linde, and J.A. Snoke. 1982. Stress redistribution and slow earthquakes. *Tectonophysics* 81(3–4):311–318, https://doi.org/10.1016/0040-1951(82)90135-4.

Saffer, D., L. McNeill, T. Byrne, E. Araki, S. Toczko, N. Eguchi, K. Takahashi, and the Expedition 319 Scientists. 2010. *Proceedings of the Integrated Ocean Drilling Program, 319*. Integrated Ocean Drilling Program Management International Inc., Tokyo, Japan.

Saffer, D.M., and H.J. Tobin. 2011. Hydrogeology and mechanics of subduction zone forearcs: Fluid flow and pore pressure. *Annual Review of Earth and Planetary Sciences* 39:157–186, https://doi.org/10.1146/annurev-earth-040610-133408.

Saffer, D.M., and L.M. Wallace. 2015. The frictional, hydrologic, metamorphic and thermal habitat of shallow slow earthquakes. *Nature Geoscience* 8(8):594–600, https://doi.org/10.1038/ngeo2490.

Saffer, D., A. Kopf, S. Toczko, and the Expedition 365 Scientists. 2017. NanTroSEIZE Stage 3: Shallow Megasplay Long-Term Borehole Monitoring System. *Proceedings of the International Ocean Discovery Program, 365*. College Station, TX, https://doi.org/10.14379/iodp.proc.365.2017.

Saffer, D.M., L.M. Wallace, K. Petronotis, and the Expedition 375 Scientists. 2018. *Expedition 375 Preliminary Report: Hikurangi Subduction Margin Coring and Observatories*. International Ocean Discovery Program, https://doi.org/10.14379/iodp.pr.375.2018.

Sagiya, T. 2004. Interplate coupling in the Kanto District, Central Japan, and the Boso Peninsula silent earthquake in May 1996. *Pure and Applied Geophysics* 161(11–12):2,327–2,342, https://doi.org/10.1007/s00024-004-2566-6.

Saito, T., K. Ujiie, A. Tsutsumi, J. Kameda, and B. Shibazaki. 2013. Geological and frictional aspects of very-low-frequency earthquakes in an accretionary prism. *Geophysical Research Letters* 40(4):703–708, https://doi.org/10.1002/grl.50175.

Sakaguchi, A., F. Chester, D. Curewitz, O. Fabbri, D. Goldsby, G. Kimura, C.F. Li, Y. Masaki, E.J. Screaton, A. Tsutsumi, and K. Ujiie. 2011. Seismic slip propagation to the updip end of plate boundary subduction interface faults: Vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTro SEIZE cores. *Geology* 39(4):395–398, https://doi.org/10.1130/G31642.1.

Satake, K. 1993. Depth distribution of coseismic slip along the Nankai Trough, Japan, from joint inversion of geodetic and tsunami data. *Journal of Geophysical Research* 98(B3):4,553–4,565, https://doi.org/10.1029/92JB01553.

Scholz, C.H. 1998. Earthquakes and friction laws. *Nature* 391:37–42, https://doi.org/10.1038/34097.

Scholz, C.H. 2002. *The Mechanics of Earthquakes and Faulting*, 2nd ed. Cambridge University Press, New York, NY.

Schwartz, S.Y., and J.M. Rokosky. 2007. Slow slip events and seismic tremor at circum-Pacific subduction zones. *Reviews of Geophysics* 45(3), RG3004, https://doi.org/10.1029/2006RG000208.

Scuderi, M.M., C. Marone, E. Tinti, G. Di Stefano, and C. Collettini. 2016. Precursory changes in seismic velocity for the spectrum of earthquake failure modes. *Nature Geoscience* 9:695–700, https://doi.org/10.1038/ngeo2775.

Shelly, D.R., G.C. Beroza, S. Ide, and S. Nakamula. 2006. Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip. *Nature* 442(7099):188–191, https://doi.org/10.1038/nature04931.

Shelly, D.R., G.C. Beroza, and S. Ide. 2007. Non-volcanic tremor and low-frequency earthquake swarms. *Nature* 446(7133):305–307, https://doi.org/10.1038/nature05666.

Shipboard Scientific Party. 2001. Leg 190 summary. Pp. 1–87 in *Proceedings of the Ocean Drilling Program, Initial Reports,* vol. 190. G.F. Moore, A. Taira, A. Klaus, eds, Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.190.101.2001.

Solomon, E.A., M. Kastner, C.G. Wheat, H. Jannasch, G. Robertson, E.E. Davis, and J.D. Morris. 2009. Long-term hydrogeochemical records in the oceanic basement and forearc prism at the Costa Rica subduction zone. *Earth and Planetary Science Letters* 282(1–4):240–251, https://doi.org/10.1016/j.epsl.2009.03.022.

Song, T.-R.A., D.V. Helmberger, M.R. Brudzinski, R.W. Clayton, P. Davis, X. Pérez-Campos, and S.K. Singh. 2009. Subducting slab ultra-slow velocity layer coincident with silent earthquakes in southern Mexico. *Science* 324(5926):502–506, https://doi.org/10.1126/science.1167595.

Spinelli, G.A., Saffer, D.M., and M.B. Underwood. 2006. Hydrogeologic responses to three-dimensional temperature variability, Costa Rica subduction margin. *Journal of Geophysical Research* 111(B4), https://doi.org/10.1029/2004JB003436.

Sugioka, H., T. Okamoto, T. Nakamura, Y. Ishihara, A. Ito, K. Obana, M. Kinoshita, K. Nakahigashi, M. Shinohara, and Y. Fukao. 2012. Tsunamigenic potential of the shallow subduction plate boundary inferred from slow seismic slip. *Nature Geoscience* 5(6):414, https://doi.org/10.1038/ngeo1466.

Tobin, H.J., and D.M. Saffer. 2009. Elevated fluid pressure and extreme mechanical weakness of a plate boundary thrust, Nankai Trough subduction zone. *Geology* 37(8):679–682, https://doi.org/10.1130/G25752A.1.

Underwood, M.B. 2007. Sediment inputs to subduction zone: Why lithostratigraphy and clay mineralogy matter. Pp. 42–85 in *The Seismogenic Zone of Subduction Thrust Faults*. T.H. Dixon and J.C. Moore, eds, Columbia University Press, New York.

Vallee, M., J.M. Nocquet, J. Battaglia, Y. Font, M. Segovia, M. Regnier, P. Mothes, P. Jarrin, D. Cisneros, S. Vaca, and H. Yepes. 2013. Intense interface seismicity triggered by a shallow slow slip event in the Central Ecuador subduction zone. *Journal of Geophysical Research* 118(6):2,965–2,981, https://doi.org/10.1002/jgrb.50216.

Wallace, L.M., and J. Beavan. 2006. A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand. *Geophysical Research Letters* 33, L11301, https://doi.org/10.1029/2006GL026009.

Wallace, L.M., and J. Beavan. 2010. Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand. *Journal of Geophysical Research* 115(B12), B12402, https://doi.org/10.1029/2010JB007717.

Wallace, L.M., J. Beavan, S. Bannister, and C. Williams. 2012. Simultaneous long-term and short-term slow slip events at the Hikurangi subduction margin, New Zealand: Implications for processes that control slow slip event occurrence, duration, and migration. *Journal of Geophysical Research* 117, B11402, https://doi.org/10.1029/2012JB009489.

Wallace, L.M., S.C. Webb, Y. Ito, K. Mochizuki, R. Hino, S. Henrys, S.Y. Schwartz, and A.F. Sheehan. 2016. Slow slip near the trench at the Hikurangi subduction zone, New Zealand. *Science* 352(6286):701–704, https://doi.org/10.1126/science.aaf2349.

Wang, K. 2004. Applying fundamental principles and mathematical models to understand processes and estimate parameters. Pp. 376–413 in *Hydrogeology of the Oceanic Lithosphere*. E.E. Davis and H. Elderfield, eds, Cambridge University Press, Cambridge.

Yokota, Y., T. Ishikawa, S.I. Watanabe, T. Tashiro, and A. Asada. 2016. Seafloor geodetic constraints on interplate coupling of the Nankai Trough megathrust zone. *Nature* 534(7607):374–377, https://doi.org/10.1038/nature17632.

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