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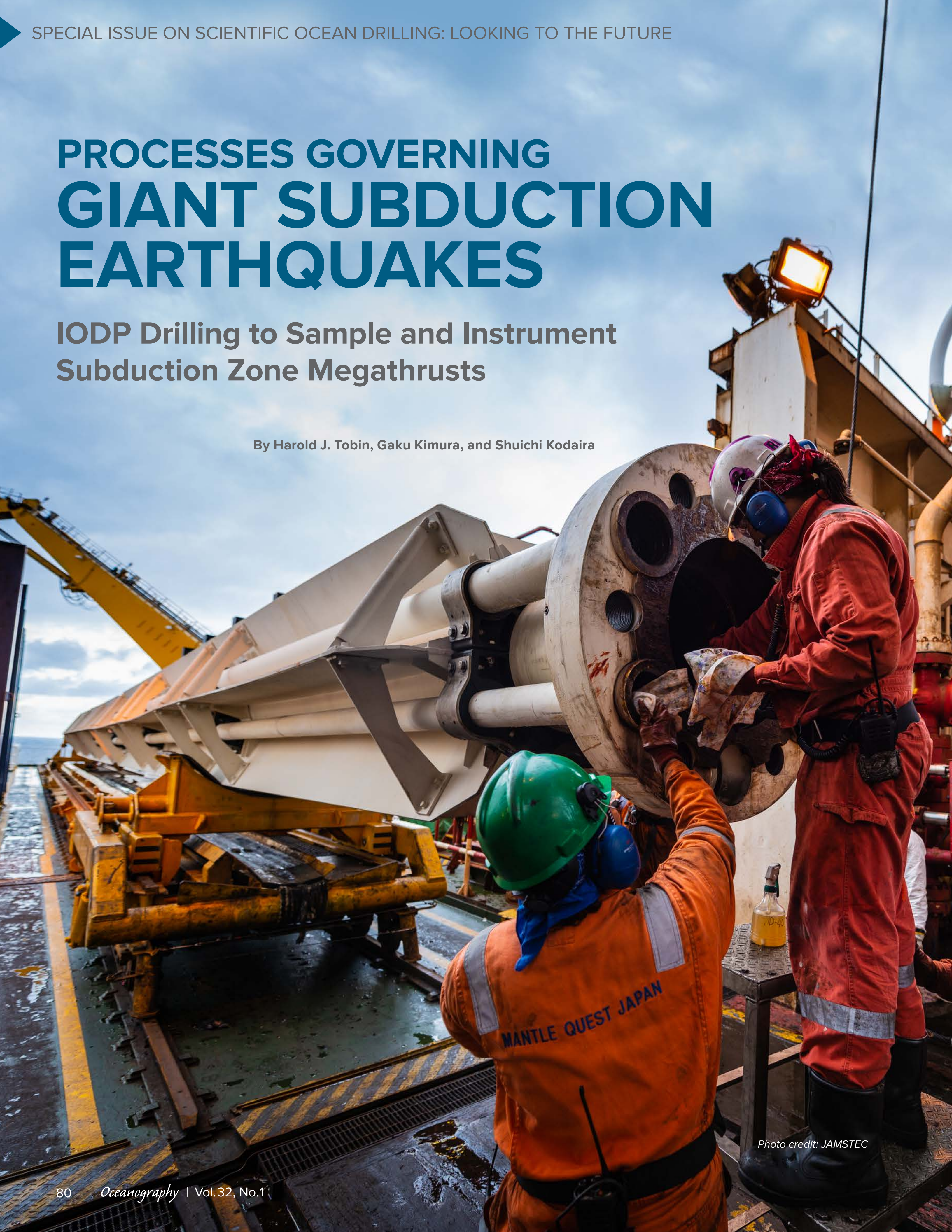
PROCESSES GOVERNING GIANT SUBDUCTION EARTHQUAKES

IODP Drilling to Sample and Instrument Subduction Zone Megathrusts

By Harold J. Tobin, Gaku Kimura, and Shuichi Kodaira



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ABSTRACT. Scientific ocean drilling from 2007 through 2018 has played a major role in an ongoing revolution in the understanding of plate boundary fault zone mechanics, structure, and associated megathrust earthquake processes and the tsunamis they create. Major efforts at the Nankai, Costa Rica, Sumatra, and Japan Trench subduction zones that have employed both the riser Japanese drillship *Chikyu* and the riserless US drillship *JOIDES Resolution* have sampled main plate boundary faults (décollements), associated splay faults, and incoming plate sediments and basement rocks that develop into the fault system. Research on these rocks and in the boreholes shows that great earthquake ruptures not only can slip all the way to the tip of the megathrust at the seafloor in some events but may well do so typically. One location on a plate boundary fault can apparently also exhibit a range of behaviors over the course of a seismic cycle, from slow slip and tremor to rapid coseismic slip, depending on state of stress, pore pressure, and acceleration interacting with intrinsic lithologic properties. Scientific ocean drilling has provided data and samples for laboratory tests of frictional mechanics, for numerical modeling of fault processes, and for testing new hypotheses on megathrust fault processes, thus playing a central role in the modern pursuit of the grand challenge of understanding how faults that are capable of generating giant subduction earthquakes work.

INTRODUCTION

Drilling to understand megathrust earthquake processes and fault zone properties has been a major focus of both the Integrated Ocean Drilling Program and the International Ocean Discovery Program (IODP), and was a primary justification for the construction of the riser drilling vessel *Chikyu*. In 2004, not long after publication of the Integrated Ocean Drilling Program Initial Science Plan, in which that objective was identified as a central strategic scientific goal of the program (Coffin et al., 2001), the Sumatra-Andaman earthquake and devastating tsunami occurred. It was Earth's first magnitude 9 earthquake *and* first ocean-basin spanning tsunami in over 40 years, since the 1964 Alaska earthquake. By the time it happened, plans were well under way for scientific ocean drilling in the Nankai Trough during the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), and drilling proposals had been submitted for the Costa Rica Seismogenesis Project (CRISP) as well. Since 2004, several other giant subduction earthquakes and tsunamis have occurred, most notably the Tōhoku event of March 2011 in the Japan Trench.

During the IODP era of scientific ocean drilling, there has been a sustained effort to access the geologic record of megathrust processes as well as the active deformational signals (strain and pore pressure transients, seismic activity, and fluid and heat transport) from the accessible portions of these subduction plate boundary fault systems. Both riserless and riser expeditions have been undertaken to study fault processes at the Sumatra, Costa Rica, Nankai, and Japan Trench subduction zones, as well as a very recent Hikurangi Trough effort (see Wallace et al., 2019, in this issue).

Collectively, these drilling-based projects contributed significantly to a revolution in understanding of how fault locking, slip, and friction work. For example, based on samples of shallow (<1 km below the seafloor) thrust faults recovered during NanTroSEIZE IODP Expedition 316, Sakaguchi et al. (2011) and Yamaguchi et al. (2011) discovered evidence for frictional heating during past fault slip, indicative of seismic rupture reaching the trench. Prior to this work, the typical view was that rapid slip was unlikely to propagate shallowly, and such a claim was controversial when published. Just three days later, the Tōhoku earthquake occurred hundreds of kilometers away in the Japan Trench. Geomorphic, geodetic, and seismologic evidence soon showed that 50 m or more of rapid frictional slip clearly reached the tip of the plate boundary fault during that earthquake, vividly confirming the new view suggested by the Nankai results. IODP drilling on Expedition 343 (JFAST) provided in situ temperature measurements, confirming frictional heating during fault slip and collecting fault zone samples that documented the signature of past high temperature friction.

Another key related advance from IODP Expedition 362 (Sumatra trench) in 2016 documents that diagenetic alteration of thick sedimentary accumulations entering the subduction trench—for example, the formation of cements—can also create frictional conditions conducive to seismic slip right to the tip of the fault (Hüpers et al., 2017). Furthermore, investigation of lithologically diverse sediments where the plate boundary fault initially forms in the sedimentary sequence off Costa Rica (Expeditions 334 and 344 in 2011 and 2012, respectively) points to differences in favorability of clay-rich vs. carbonate-rich sediments in promoting rapid and seismic vs. slow and/or aseismic slip to the trench at that subduction margin. At larger spatial and temporal scales, three-dimensional seismic imaging and drilling results from the Costa Rica margin have led to reevaluation of the subduction erosion hypothesis in favor of episodic bursts of vertical uplift and collapse of the margin without necessarily requiring net tectonic removal of the forearc from below (Edwards et al., 2018).

Taken together, the intensive study of the Sumatra, Costa Rica, Nankai, and Japan Trench subduction systems has played a major role in the development of a new view of the mechanics and behavior of the upper portions of subduction zone plate boundary faults. Here, we review some of the major findings of IODP drilling from these four subduction systems and allied research in each of them to highlight common themes that have emerged. All of the IODP expeditions have produced a wide range of additional results that are relevant to IODP themes, particularly the tectonic evolution of accretionary and non-accretionary margins, but these topics are beyond the scope of this review.

NanTroSEIZE: SAMPLING FAULTS AND OBSERVING TRANSIENT SLIP AT THE SHALLOW END OF THE PLATE BOUNDARY

The Nankai Trough is formed by subduction of the Philippine Sea Plate to the northwest beneath the Eurasian Plate at a local calculated rate of 5.8 cm yr^{-1} (Figure 1; DeMets et al., 2010). With its ~1,300 year historic record of great (M_w > 8.0) earthquakes that are typically tsunamigenic (Ando, 1975; Hori et al., 2004), this margin was deemed especially favorable for study of a seismogenic zone through drilling. The plate boundary here is nearly fully locked (lacking aseismic or slow slip on the main megathrust) and is in the mid to late interseismic stage (i.e., close in time to the next expected major earthquake). However, a recent offshore acoustic GPS geodetic study suggests that the Kumano region (southeast of the Kii peninsula), where the NanTroSEIZE transect is located, may be locked to a lesser degree than other parts of this subduction zone (Yokota et al., 2016), consistent with observations of slow transient slip and very low-frequency local earthquakes (Sugioka et al., 2012; Araki et al., 2017; also see below for discussion).

The NanTroSEIZE Complex Drilling Project (CDP), the largest project in the history of scientific ocean drilling, has included 11 IODP expeditions and more than 200 scientists. It began in 2007 and continues today, with IODP Expedition 358, which began in October 2018 and is scheduled to continue through March 2019. It. Its transect includes full drilling of the incoming plate section and upper igneous basement through the frontal thrust and out-of-sequence or "megasplay fault" region, as well as ultradeep drilling at two sites (C0002 and C0009) in the Kumano forearc basin (Figure 2). Site C0002 includes the deepest scientific ocean drilling hole ever

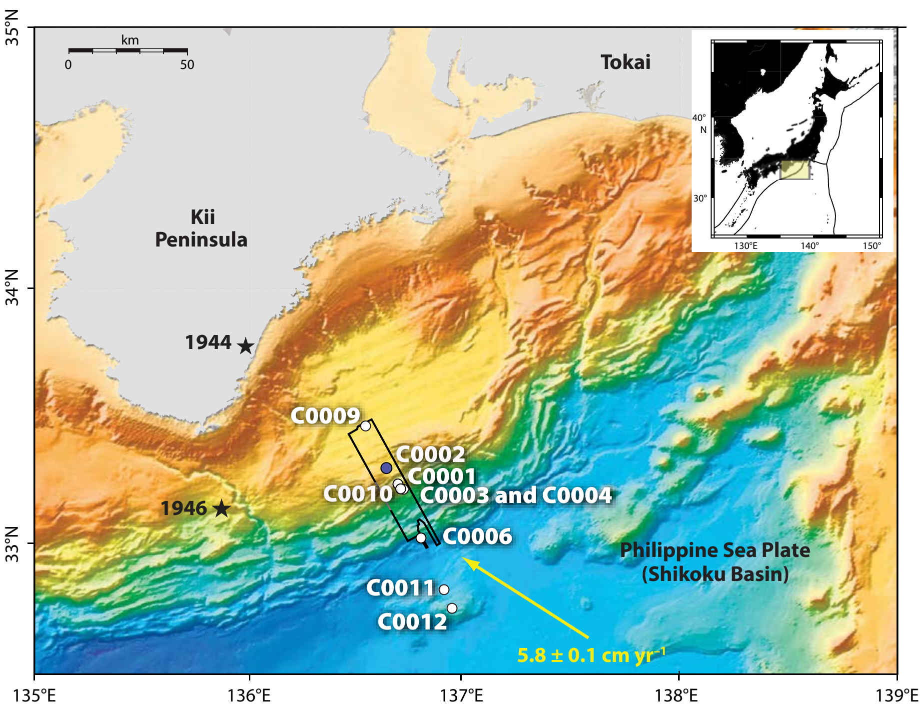


FIGURE 1. Location map of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) drilling transect area in the central-eastern Nankai Trough off the Kumano region, Japan. Numbered IODP sites are shown, as is the three-dimensional seismic footprint (box). Stars indicate the epicentral positions of the 1944 and 1946 great megathrust earthquakes. The yellow arrow shows the direction of relative plate convergence across the Nankai Trough of DeMets et al. (2010). *After Tobin et al. (2014)*

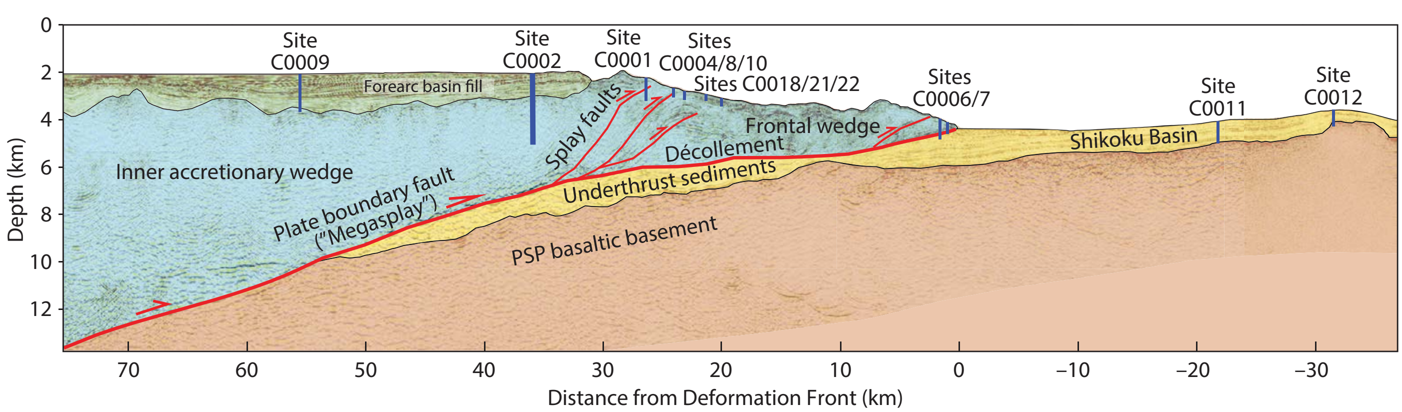


FIGURE 2. Interpreted seismic depth section through the NanTroSEIZE drilling area, after Park et al. (2002) and Moore et al. (2009). *Adapted from Tobin et al. (2014)*

undertaken, extending to 3,056 meters below the seafloor (mbsf), with plans for deepening to 5,200 mbsf during Expedition 358. NanTroSEIZE scientists also installed an advanced real-time borehole observatory for geodesy, pore pressure, and seismic observations at more than 800 mbsf. Overviews of the tectonic and geologic results of this transect were published in Tobin et al. (2014) and in Underwood and Moore (2012); here, we review the specific results regarding past and present dynamic fault activity.

Among the most remarkable results of NanTroSEIZE drilling to date is the discovery that fault slip at the frontal thrust (Site C0007) and megasplay (Site C0004) is apparently extremely localized in millimeters-thick faults that exhibit evidence of shear-related heating believed to result from slip at tsunamigenic to (potentially) earthquake speeds (centimeters per second to meters per second). As synthesized by Ujiie and Kimura (2014), at both fault drill penetrations, very fine-grained fault gouge several millimeters to 1 cm thick were found embedded in wider zones of fractured and brecciated rocks (Figure 3). The dark gouge zone at 438 mbsf at the frontal thrust (Site C0007) is 2 mm thick and bounded by sharp planar surfaces; it marks a biostratigraphically determined 1.67 million year age reversal. Along with several additional thin dark gouge zones in the same interval, it has accommodated ~6 km of slip (Screaton et al., 2009). These observations indicate that this is the main plate boundary thrust, and it shows strong localization of faulting over hundreds of earthquake cycles.

Studying these gouge zones in detail, Sakaguchi et al. (2011) found anomalies in vitrinite (organic matter) reflectance values from which they estimated that the fault gouges had been subject to 330°–390° ± 50°C temperatures, compared to an ambient background of only ~20°C, probably consistent with frictional heating that only occurs during rapid slip (Fulton and Harris, 2012). This result was further corroborated by X-ray fluorescence and X-ray diffraction data from the core taken across the gouge zones, which revealed geochemical variation consistent with the preferential occurrence of illite in the fault gouge clays as compared to the surrounding breccia (Yamaguchi et al., 2011), also a possible result of frictional heating.

Taken together, these detailed studies of the gouge deformational fabrics, strong localization, and geochemical proxies for frictional heating suggest that past Nankai earthquake-speed fault rupture propagated all the way to the trench, at least in one or more past events, and also all the way to the seafloor at the drilled megasplay fault.

Low-angle thrust slip has long been considered to be possible only in the presence of strongly elevated pore fluid pressure (Hubbert and Rubey, 1959), and evidence for high pore pressure in accretionary wedge settings has been much discussed and sought (see Saffer and Tobin, 2011, for a review). However, there is little direct evidence of anything more than very modest pore pressure above hydrostatic ("normal") levels in the fault zones drilled so far. Direct downhole pressure monitoring within the megasplay fault at ~410 mbsf at Site C0010 documented pore pressure slightly in excess

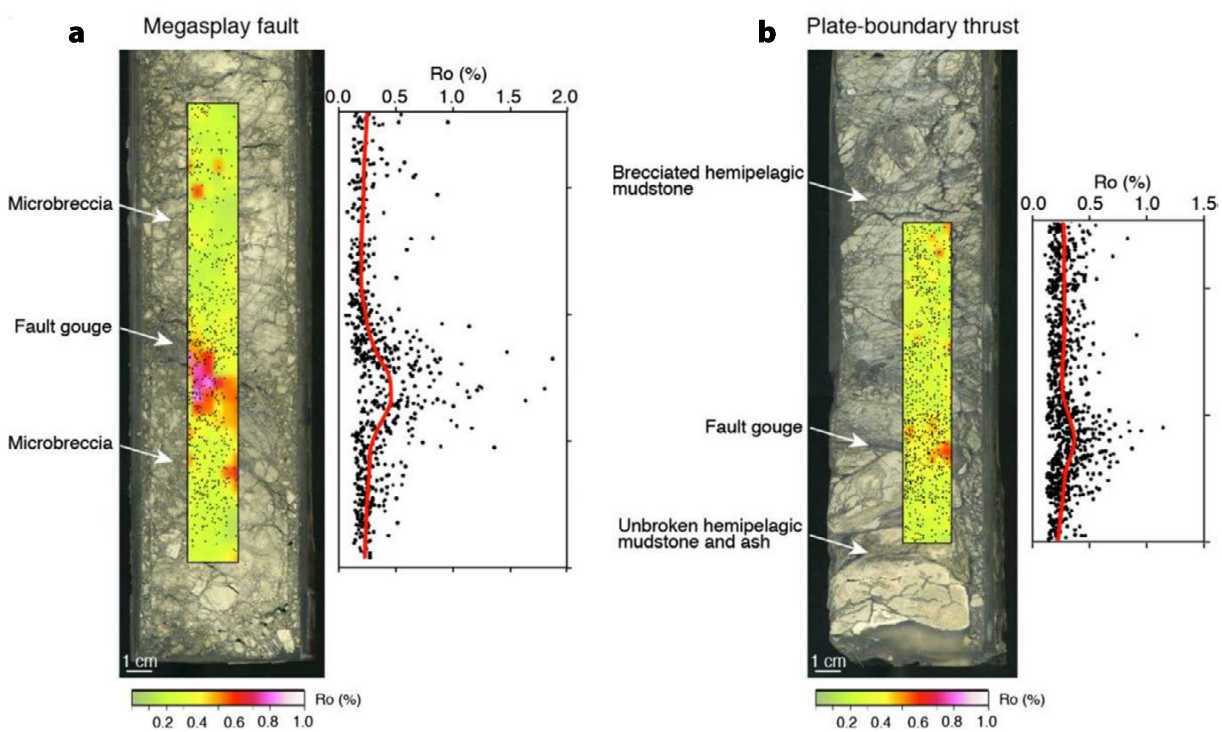


FIGURE 3. Vitrinite reflectance data from Sakaguchi et al. (2011), superimposed on images of the fault zone core from (a) the Site C0004 splay fault, and (b) the Site C0007 frontal thrust fault. *After Ujiie and Kimura (2014).*

of hydrostatic (Hammerschmidt et al., 2013). This result is consistent with shipboard porosity data that show no indication of excess porosity (hence high pore pressure) beneath the shallow megasplay (Screaton et al., 2009). There is similarly no direct physical property evidence nor indirect geochemical signs of elevated pore pressure in the frontal thrust region. Seismic velocity inferences suggest, however, that pore pressures may be high at levels deeper than drilling has reached so far (Park et al., 2010; Kitajima and Saffer, 2012).

Perhaps the most groundbreaking result of the NanTroSEIZE project to date is the insight gained from installation of deep borehole observatories that stream data in real time to shore via the Japanese DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) cable system. At Sites C0010A and C0002G, IODP has installed borehole instrument packages at around 450 mbsf and 850 mbsf, respectively, in which seismic activity, strain, pore fluid pressure, and temperature are continuously monitored (Kopf et al., 2016; Araki et al., 2017). The two sites are 11 km apart in the dip direction, spanning the outer limits of the zone believed to be locked and seismogenic. These are the first real-time deep ocean subduction zone observatories of their kind.

Along with the dense seafloor array of broadband seismometers in the NanTroSEIZE/DONET region, these borehole observatories have permitted direct and real-time observation of transient slow slip events on the shallow, updip edge of the locked plate boundary fault. In particular, pore fluid pressure observations made in a sealed, low-permeability interval of the sedimentary formation that overlies the plate boundary in the upper plate wedge (Figure 4) have proven to be effective proxies for volumetric strain. Araki et al. (2017) identified eight recurring transient strain events accompanied by low-frequency tremor and very low-frequency earthquakes in the period between 2012 and 2016, each representing several centimeters of slip, most likely on the plate boundary, and lasting days to weeks. The first such transient events captured offshore Nankai were calculated to account for 30%–55% of the total plate motion (Araki et al., 2017). Along with previous pioneering detections of shallow transient slip events that occurred offshore Costa Rica (Brown et al., 2005; Davis et al., 2011, 2015) and Nankai in the

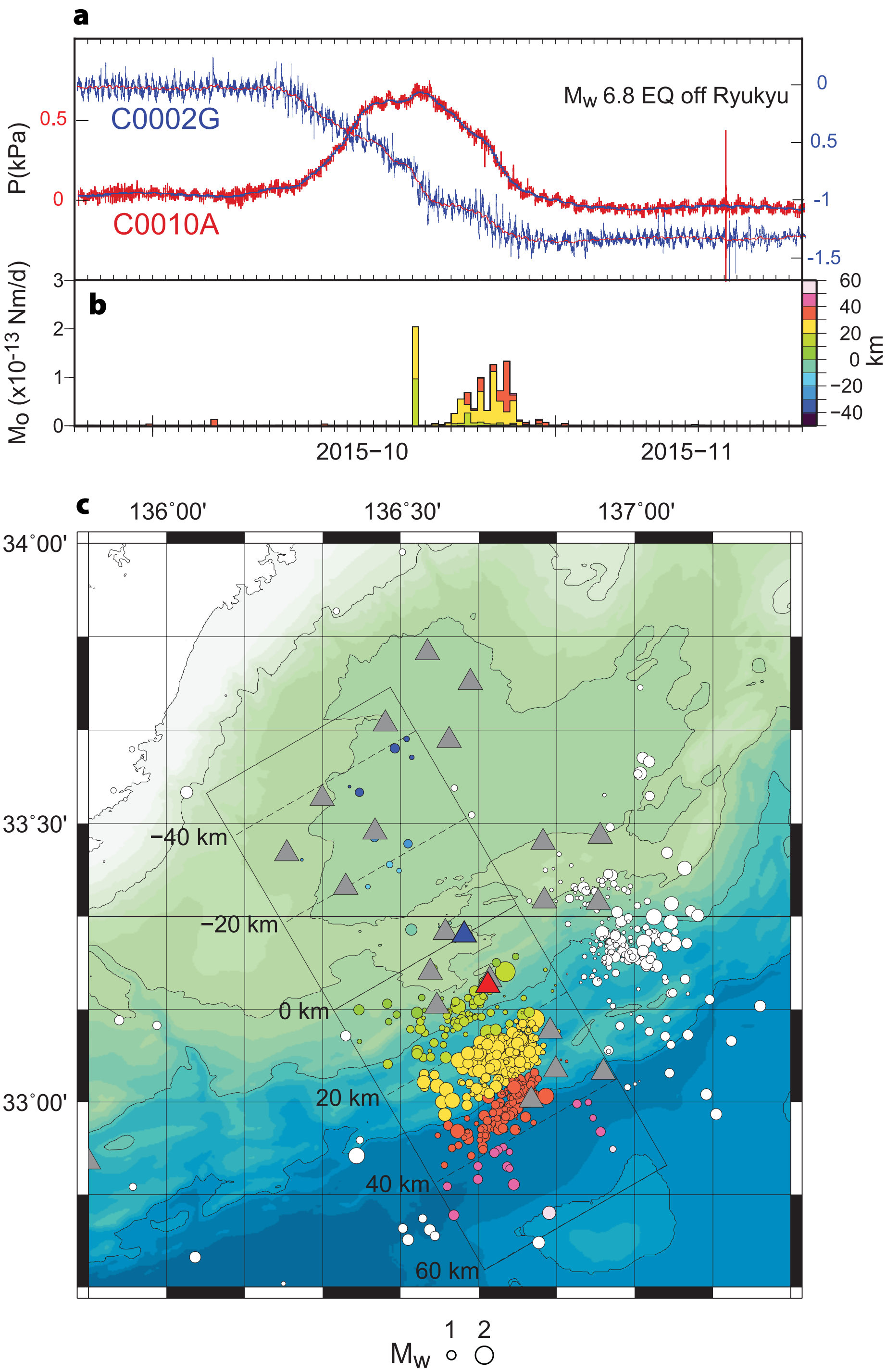


FIGURE 4. Observations of one example of a slow slip transient event. (a) Pore fluid pressure observations in the screened interval at the two borehole observatories installed as part of NanTroSEIZE and connected to the Japanese Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) real-time seafloor cable observatory. (b) Time series of the moment release by low-frequency tremor during the same interval as recorded on the seafloor network and binned in color by distance from the C0002G observatory. (c) Same low-frequency tremor data set shown spatially, along with locations of ocean bottom seismometer stations (triangles). *After Araki et al. (2017)*

Muroto region southwest of Japan (Davis et al., 2013), they represent an entirely new window into real-time deformation beneath the ocean floor.

The twin discoveries that (1) fast seismic slip has taken place at even shallow levels of the main frontal thrust and the major splay faults, and (2) slow slip, tremor, and very low-frequency earthquakes occur on the regional plate boundary fault directly beneath the observatories implies that *the same fault system hosts both fast and slow slip in the same place at different times through an earthquake cycle*, upending the idea that faults are intrinsically of seismic or aseismic type. This is strong evidence for the emerging view of rate-state frictional behavior as conditional, as opposed to an intrinsic property of a particular fault zone lithology.

The borehole observatories are capturing the spectrum of fault locking and strain release on short timescales, apparently right where the fault is transitioning from its shallow and conditionally stable regime to the zone of seismogenic frictional locking and instability, as envisioned by Saffer and Tobin (2011) and others in recent years. This is an unprecedented real-time view of the faulting process. Recent observations of slow slip transient behavior and swarms of foreshocks before the Tōhoku and Iquique (Chile) megathrust earthquakes have been hypothesized as precursory phenomena that could one day be used as an early warning tool (Kato, 2012; Brodsky and Lay, 2014), but that require just the sort of observations that the NanTroSEIZE observatories are now providing.

SUMATRA: DRILLING THE INCOMING PLATE AND POTENTIAL DÉCOLLEMENT HORIZON

The M_w 9.2 Sumatra-Andaman earthquake on December 26, 2004, which generated a disastrous tsunami (Stein and Okal, 2005), was one of the three largest recorded earthquakes in history. The rupture propagated ~1,300 km along strike from offshore northern Sumatra to the Andaman Islands located on the Burma-Sunda Plate. Three months later, on March 28, 2005, it was followed by an M_w 8.7 earthquake ~400 km to the south of the 2004 hypocenter off Nias island (e.g., Briggs et al., 2006) and then a series of plate boundary ruptures in 2007 and 2010 (Figure 5).

Ocean drilling sites in the Indian Ocean prior to the 2004 Sumatra-Andaman earthquake were mainly located on the Bengal-Nicobar Fan and the Ninety East Ridge, where drilling was designed to reveal the links between Himalayan tectonics and the climate of Asian monsoon (Deep Sea Drilling Project Leg 22, Ocean Drilling Program [ODP] Legs 116 and 121, and IODP Expedition 353 and 354). IODP Expedition 362 targeted two drilling sites on the incoming plate in order to reveal what factors controlled the 2004 great earthquake and tsunami in relation to the development of the Bengal-Nicobar Fan and the huge accretionary prism characteristic of the hanging wall of the rupture area of the 2004 earthquake (Dugan et al., 2017).

Geophysical and geological data sets acquired immediately after the 2004 earthquake showed that trench-filling sediments overlie ~1.5 km of Nicobar Fan deposits such that a total thickness of more than 4 km are present in the Sumatra trench (Figure 6; Henstock et al., 2006; Singh et al., 2008; Dean et al., 2010). In addition, structural features show that the 2004 tsunami-generating rupture area is characterized by landward-vergent thrusts (i.e., "backthrusts" relative to the underlying plate boundary megathrust) around the deformation front, whereas the 2005 deformation front off Nias island is a seaward-vergent fold-and-thrust system, as is more common in accretionary prisms (Henstock et al., 2006; Dean et al.,

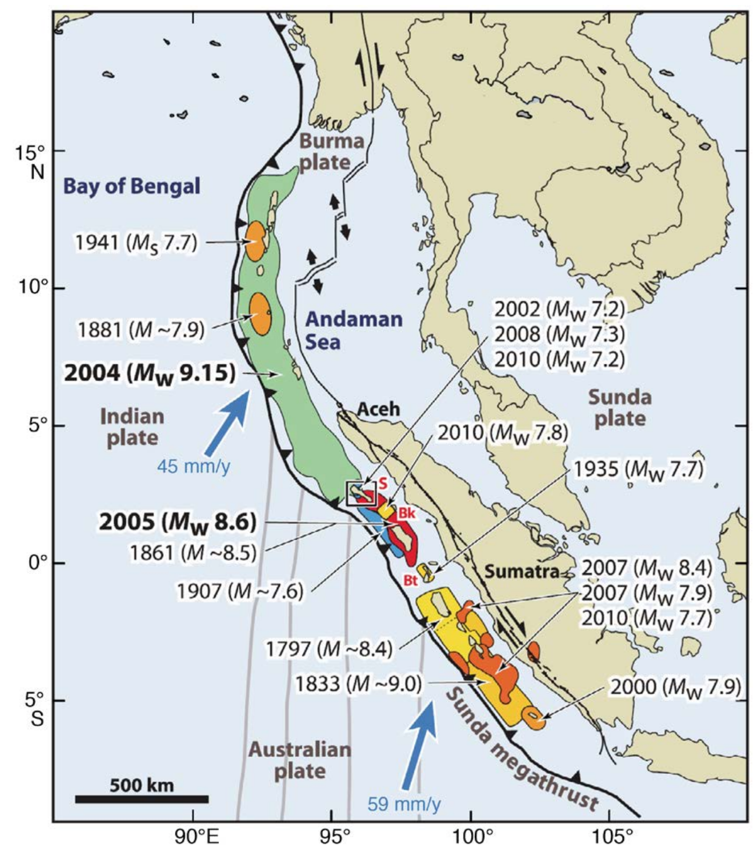


FIGURE 5. Tectonics and seismic history of the Sumatra margin and Sunda megathrust region. Rupture areas of historical megathrust earthquakes (M > 7) are shown. Plate convergence vectors are in blue. Black lines are faults, and gray lines are fracture zones. *After Dugan et al. (2017)*

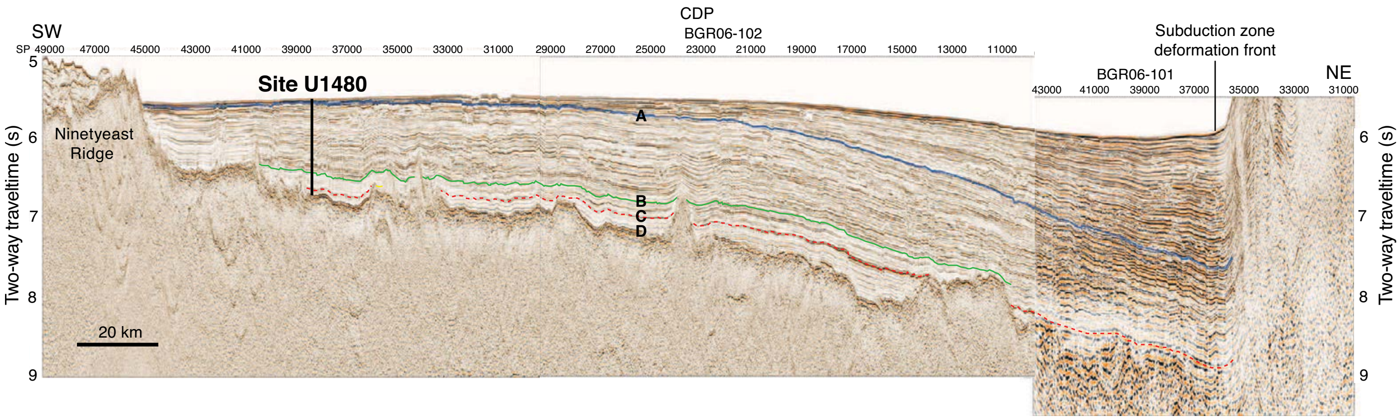


FIGURE 6. Composite seismic reflection profile of IODP Expedition 362 area targeting the incoming plate sedimentary section and upper igneous basement rocks at Site U1480. Letters A to D denote seismic horizons, where A (blue line) is the base of the trench wedge, C (dashed red line) is the potential décollement horizon, and D is the top of igneous oceanic basement. *After Dugan et al. (2017, references therein)*

2010; Moeremans et al., 2014). A sudden uplift of the accretionary prism likely generated the tsunami when slip propagated to (or near to) the trench. High seismic velocity in the large, thick accretionary wedge led to hypotheses that the wedge is unusually strong in bulk properties, promoting large slip and seafloor uplift (Gulick et al., 2011). Scientific questions for Expedition 362 drilling were therefore: What were the physical properties and conditions of the plate boundary décollement and frontal thrust beneath the thick sediments, and what was the specific geological effect of development of Nicobar Fan on the development of the accretionary prism and the occurrence of the great earthquake and tsunami?

Drill Site U1480 (and similar Site U1481) of IODP Expedition 362 are located in the Nicobar Fan east of the Ninety East Ridge offshore north Sumatra (Figure 5). The very thick trench wedge (everything above horizon A in Figure 6) precluded drilling to the décollement at the deformation front, so the strategy was to drill the lower part of the incoming plate section distal to the thrust front, where the lower section—laterally equivalent to the plate boundary fault décollement horizon—is accessible. A complete sedimentary section of the interval and basement rocks was recovered. Sediments between horizons A and C represent the Nicobar turbiditic fan, underlain by pelagic sediments that in turn overlie igneous basement (horizon D). Compositional analysis of the Nicobar Fan section documents that the sediment supply increased dramatically in the ~9.5 Ma to ~2 Ma interval from the Eastern Himalaya and Indo-Burmese wedge on land to the north (McNeill et al., 2017). Tectonic and climate linkage producing a punctuated sediment supply is clearly documented. As the Late Cenozoic main sediment source of the accretionary wedge of the Sumatra forearc is likely to be the Bengal- and Nicobar Fan, this history is quite significant to understanding the onset of the forearc of the Sumatra Trench.

Two prominent structural features of the 2004 rupture area are sediments more than ~3-4 km thick in the trench and landward vergent thrusts at the deformation front (Henstock et al., 2006; Singh et al., 2008; Dean et al., 2010). Therefore, understanding the relationship of these features to the large rupture propagation is a key to understanding fault slip conditions and tsunami generation. Hüpers et al. (2017) focused on the geologic significance of the pelagic sediments beneath the Nicobar Fan and above the basement recovered by IODP Expedition 362. This interval contains horizon C (Figure 6), which represents the interpreted potential future décollement level, so its properties are of special interest for understanding the mechanical characteristics of the megathrust faulting process.

These pelagic sediments are dominantly composed of hydrous amorphous silica and altered volcanic ash-origin palagonite, including hydrous smectite. They lay with little burial on the ocean floor for more than 30 million years, then were overlain by the Nicobar Fan since ~9 million years ago, followed more recently by thousands of meters of trench filling sediments. This thick burial and loading would have increased the temperature, and complete dehydration from amorphous silica to quartz would have progressed in the now-deep sediments. Observed freshening of the interstitial fluid in this interval is a signal of this dehydration (Hüpers et al., 2017). Such rapid dehydration would increase pore fluid pressure and result in decrease of effective strength. Hüpers et al. (2017) further suggest that the seismic reflector that develops laterally landward in this horizon is due to such a reaction. The horizon extends to the décollement beneath the accretionary prism beyond the deformation front. As Hüpers et al. (2017) discuss, the dehydration would have reached completion by the time subduction delivers this section to the tip of the plate boundary fault zone, and therefore the frictional property of the décollement would likely have already transformed to an unstable (velocity weakening) state, due to precipitation of quartz, before entering the subduction fault system.

As with the Nankai margin discussion

above, the prevailing wisdom prior to this discovery held that the unstable-stable (or aseismic to seismogenic) transition along the plate boundary megathrust is located beneath the forearc wedge, but these new results from Sumatra strongly suggest that the transition is instead located beneath the thick trench filling wedge, that is, *seaward* of the wedge tip. Therefore, the entire low-angle megathrust may be in the frictionally unstable zone, with no shallow stable-sliding portion. Combined with a strong accretionary wedge (Gulick et al., 2011), this unstable fault facilitates large seismic slip and concomitant tsunamigenic uplift of the outer wedge, as suggested by seismic and geodetic inversion studies (Ammon et al., 2005; Bletery et al., 2016). Hüpers et al. (2017) suggest that this scenario could be applicable to Cascadia and other places where trench filling sediments are thick and the thrust at the deformation front shows landward vergence.

MIDDLE AMERICA TRENCH: CRISP DRILLING OF THE OSA PENINSULA TRANSECT

At the Middle America Trench, subduction erosion has long been hypothesized to take place during convergence of the Caribbean and Cocos Plates (Figure 7). The processes associated with subduction erosion were investigated during IODP Expeditions 334 and 344, as well as with a 2011 three-dimensional seismic reflection survey (Bangs et al., 2014; Edwards et al., 2018). The history and persistence of subduction erosion vs. accretion have long been debated for the Costa Rica margin, in particular, as well as the prevalence of these processes globally. At the ODP Leg 170 Nicoya Peninsula transect along strike to the northwest, subsidence of the forearc was suggested to result from long-term subduction erosion at this margin (Vannucchi et al., 2001). Based on this older work, the Costa Rica margin has come to be seen as a prime example of long-term subduction erosion processes.

IODP Expeditions 334 and 344 targeted the Middle America Trench off the Osa Peninsula of southern Costa Rica (Vannucchi et al., 2013; Harris et al., 2013, respectively) as the first stage of the Costa Rica Seismogenesis Project (CRISP; Figure 8). The setting for these expeditions is a region of the trench where the Cocos Ridge collides with and subducts beneath the Osa Peninsula of the Caribbean Plate.

Seismic imaging showed that the main forearc inner wedge is composed of layered sedimentary material rather than old crystalline forearc crust as believed

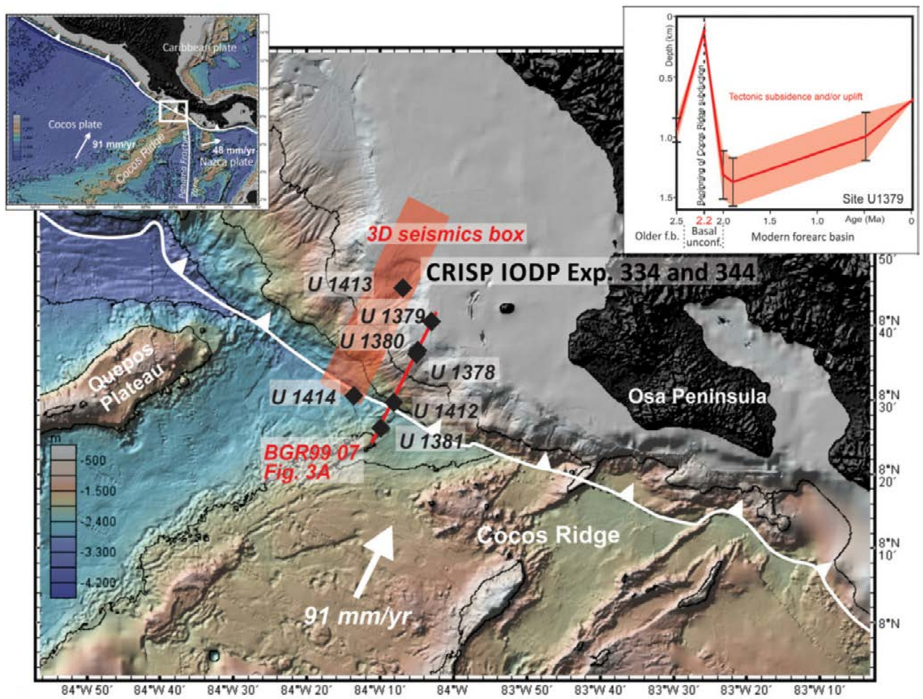


FIGURE 7. Costa Rica Seismogenesis Project (CRISP) IODP drilling area and tectonic setting. Location of seismic line BGR99-07 (Figure 8) marked in red. *After Vannucchi et al. (2016)*

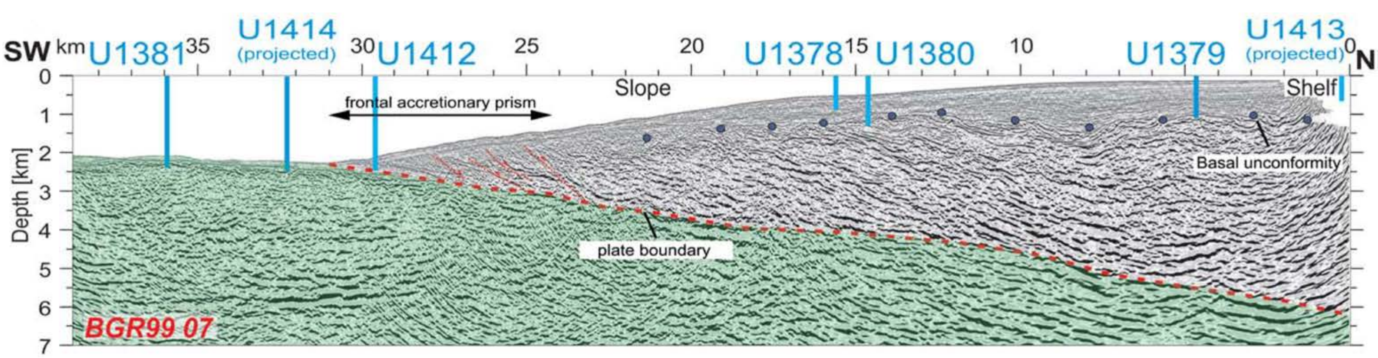


FIGURE 8. BGR99 07 depth-processed seismic line with IODP Expedition 334 and 344 drill sites. Line location is shown in Figure 7. Subducting lower plate is masked in green. The high-amplitude reflector at the base of the slope sediments is marked by blue dots, and underlain by older forearc basin fill. *After Vannucchi et al. (2016)*

for the ODP Nicoya transect (Bangs et al., 2014). Interpreting drilling results in light of that seismic evidence, Vannucchi et al. (2016) proposed a new paradigm they call a "depositionary margin," defined as a subduction zone where extreme basal tectonic erosion removes the entire forearc crust concurrently with rapid forearc basin filling by terrigenous input from the continent, leaving a deep basinal section underlain directly by the downgoing plate and plate interface fault.

In a new analysis of the drilling results and seismic imaging, Edwards et al. (2018) re-interpreted the tectonic history recorded by the basin and wedge of the Osa region. By tying basinal sequence analysis to stratal ages obtained from analysis of drill cores, they showed that this region has undergone rapid, geologically brief periods of uplift and subaerial erosion plus collapse and basin deposition throughout the Pleistocene, as lower plate topographic features have entered and passed through the subduction zone. They show that basal tectonic erosion and landward retreat of the margin are neither required nor likely, contrary to previous models that propose wholesale tectonic erosion here. These results may prove to have implications for the tectonic erosion model more generally.

The results of IODP scientific ocean drilling in the Middle America Trench have also contributed insights into seismogenesis in subduction zones. The Middle America Trench is characterized by active seismicity (e.g., Protti et al., 1995; Deshon et al., 2003, 2006; Arroyo et al., 2014), but historically does not generate M8 and larger great earthquakes. A key element here is the relationship between the subduction of topographic highs—seamounts, which typify this margin—and the nucleation and propagation of earthquakes. Prevailing wisdom has held that a seamount is an asperity (an area where the fault is locked) in the seismogenic zone (Cloos, 1992; Scholz and Small, 1997); when this locked asperity fails, rupture would then propagate away from the seamount region, resulting in a large-magnitude earthquake. Wang and Bilek (2011) put forth an alternative hypothesis, suggesting that seamount subduction instead promotes aseismic creep and relatively small earthquakes, not large ruptures. These hypotheses are compatible if it is recognized that magnitude 6.5–7.5 earthquakes are, in fact, small events from the megathrust perspective and scale.

As with Nankai, Sumatra, and the Japan Trench, the materials in the plate boundary fault zone and their frictional properties have been studied in detail to shed light on the fault rupture process. Ikari et al. (2013) proposed another, mineralogically grounded, hypothesis on the question of whether subducted seamounts are asperities or whether they promote weak, quasi-aseismic zones. On the basis of friction experiments using IODP samples, these authors argue that the carbonate sediment cap typical above seamounts facilitates seismic slip because chalk is frictionally strong and velocity weakening (a term that connotes that the material loses shear strength with increasing slip speed). Based on these experimental results, Vannucchi et al. (2017) suggested carbonate sediments in the plate boundary fault might promote slip to the trench, in contrast to clay-rich sediments. Both sediment types exhibit velocity weakening under fast (seismic) rupture (~m s^{-1}) experimental conditions, but carbonate ooze is much weaker than clayey sediments. During slow slip, on the other hand, clayey sediments show velocity strengthening while carbonate ooze still shows velocity weakening (Ikari et al., 2013). Note that under those slow slip conditions, their strength is opposite: the clay is weaker than the carbonates. Combining the results of friction experiments with analysis of three-dimensional seismic profiles that show the plate boundary décollement is located within the carbonate horizon and extends to the deformation front, Vannucchi et al. (2017) suggest that in the Osa region, rapid slip would propagate to the trench, similar to observations of the 2011 Tōhoku earthquake.

JFAST: THE JAPAN TRENCH FAST DRILLING PROJECT

A striking observation from the 2011 Tōhoku-oki earthquake was the very large fault slip that reached the shallowest part of the subduction zone in the Japan Trench (e.g., Lay et al., 2011). Comparison of bathymetry measured before and after the earthquake showed ~50 m of trenchward seafloor displacement (Fujiwara et al., 2011) caused by coseismic slip along a seafloor-breaching fault at the trench axis (Kodaira et al., 2012). The large shallow fault slip generated the more than 10 m average height of the devastating tsunami (maximum >40 m) that struck the entire coastline of northeastern Japan (e.g., Fujii et al., 2011; Mori et al., 2012).

IODP Expedition 343 and 343T, the Japan Trench Fast Drilling Project (JFAST), was carried out beginning in April 2012, 13 months after the earthquake, in the large slip zone of the earthquake as IODP's first-ever "rapid response" drilling (Figure 9). In order to understand how the extremely large fault slip reached the tip of the subduction zone, JFAST drilling was planned to reach the fault at less than 1,000 mbsf with three main objectives: (1) estimate the stress state in the fault zone, (2) obtain cores from the coseismically slipped fault to examine the plate boundary structure and measure physical-chemical properties of the fault, and (3) measure in situ residual temperature anomalies across the fault zone to estimate frictional heating during the earthquake and thereby infer actual frictional properties of the fault zone during rapid slip.

The expedition had to be done as soon as possible after the earthquake and required drilling in extremely deep water (~7,000 m depth). A site was selected ~6 km from the trench axis where seismic data imaged the plate boundary at ~900 mbsf (Figure 9b). During Expedition 343, *Chikyu* successfully drilled to the fault zone. Then, a string of 50 thermistors was hung in the fault zone borehole between 650 mbsf and 820 mbsf

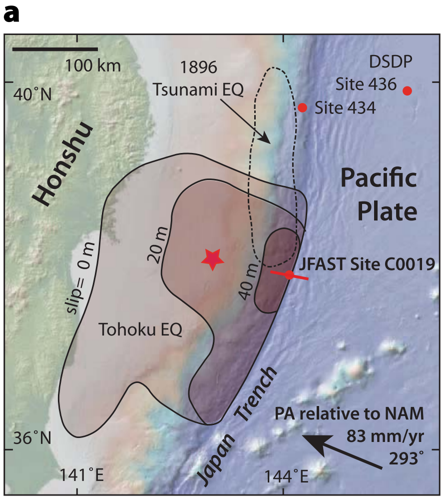
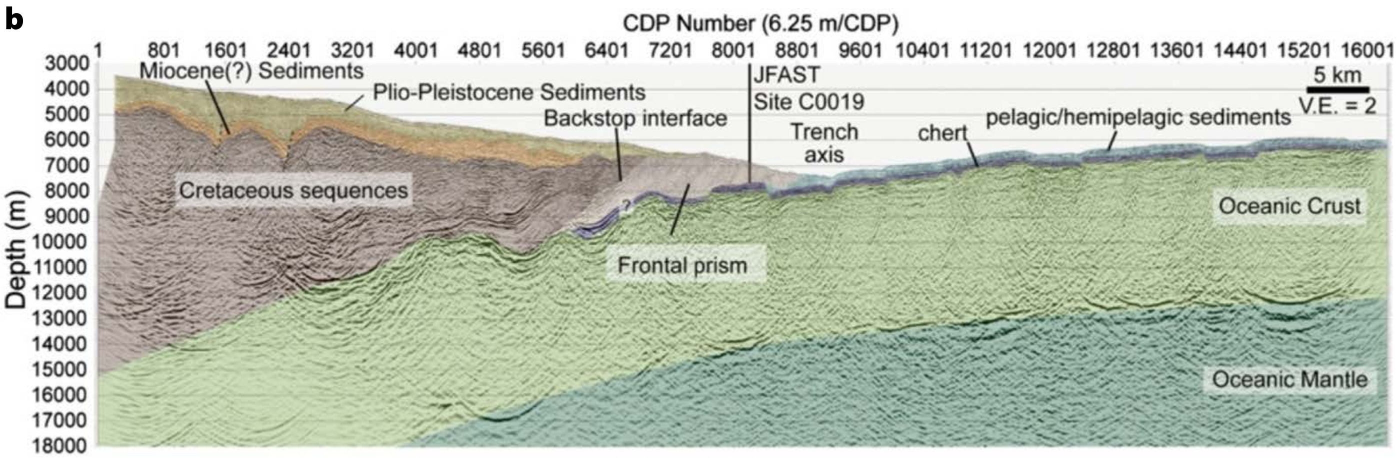


FIGURE 9. Location of the Japan Trench Fast Drilling Project (JFAST) drill site (Chester et al., 2013) and the seismic profile crossing the JFAST site (Nakamura et al., 2014). (a) The red dots indicate the location of the JFAST site (Site C0019) and previous Deep Sea Drilling Project (DSDP) sites, and the red star marks the epicenter of the 2011 Tōhoku-oki earthquake. Contours show the coseismic slip inferred from various coseismic slip models. The dashed line shows the approximate rupture zone of the 1896 Meiji-Sanriku earthquake. The red line indicates an approximate location of the seismic profile shown in (b). (b) Pre-stack depth migration image of the seismic section crossing the JFAST site and its interpretation.



on Expedition 343T in July 2012. In April 2013, after nine months of continuous temperature monitoring, the remotely operated vehicle *Kaiko* retrieved the observatory.

Geophysical logging at Site C0019 collected resistivity images of the borehole wall, including images of borehole "breakouts" (failures of the borehole wall from which stress conditions can be deduced). Based on their directions and sizes, Lin et al. (2013) concluded that the stress state in the shallow portion of the hanging wall of the rupture zone had changed from a thrust-faulting stress regime to a normal-faulting or near-normal-faulting stress regime during the earthquake. This suggested coseismic fault weakening and nearly total stress drop at the shallow portion of the large slip zone, consistent with earthquake observations (Hasegawa et al., 2011) and geodetic observations (Sato et al., 2011).

Core samples were collected from a key interval where seismic data show a strong reflector that is interpreted as the main plate boundary fault. In the cores, the fault zone was identified at ~820 mbsf by changes in geological properties, such as lithology, age, and orientation of bedding (Chester et al., 2013). The fault zone sediment consists of pelagic brown clay with a scaly fabric (Figure 10), not observed in other cores collected from the surrounding area. Although a complete section of the plate boundary fault zone was not recovered, the total thickness of the fault zone (i.e., the scaly clay layer) was estimated as less than 5 m based on analysis of the recovered core and the thickness of the un-recovered gaps. The thin nature of

FIGURE 10. Photo of the core recovered from the plate boundary fault zone showing a highly deformed scaly clay layer. *From Mori et al. (2014)*

the fault zone suggests that localization of the coseismic slip caused or contributed to the very large slip along the fault.

In order to investigate frictional properties that control slip in the shallow part of the rupture zone, Ujiie et al. (2013) carried out high velocity friction experiments on core samples collected from the scaly clay layer. They used a high-velocity, large-slip rotary shear device to conduct experiments under permeable and impermeable conditions. They set experimental parameters to be comparable to the conditions of fault motion during the earthquake (i.e., slip rate of 1.3 m s^{-1}, displacements of ~15 m to 60 m). Resultant observed steady-state shear stress under a normal stress of 2.0 MPa shows ~0.4 MPa and ~0.2 MPa for the permeable and impermeable cases, respectively (Figure 11). Under the effective normal stress of 7 MPa at a depth of 820 mbsf on the décollement at Site C0019, these results yielded 1.32 MPa and 0.22 MPa, which corresponds to apparent coefficient of friction of 0.19 and 0.03 for the permeable and impermeable cases, respectively. Ujiie et al. (2013) concluded that the measured shear strengths of samples from the plate boundary fault in the large slip zone of the Japan Trench are lower than those obtained from the fault material at Nankai Trough. Examination of the microstructures in the gouge samples following the high velocity friction experiments shows that the very low shear stress can be attributed to the smectite-rich weak clay and the expansion of pore fluids by frictional heating, known as thermal pressurization.

Finally, the JFAST project included estimation of frictional heating due to coseismic slip of the fault using long-term temperature measurements collected by an array of borehole instruments. The frictional shear stress—and therefore the effective coefficient of friction—can be estimated from the temperatures measured along the fault if the coseismic fault slip is known. Because the temperature increase along the fault during the earthquake was very large (hundreds of degrees), it was expected that residual (albeit small) temperature anomalies would be observed even one or two years later.

Depth versus time and temperature was plotted, revealing a small temperature anomaly at the plate boundary fault (Figure 12; Fulton et al., 2013). After removal of the background geothermal gradient, the plot shows values 0.3°C higher at 814–820 mbsf than temperatures at shallower depths. It took about two months for the temperatures to equilibrate in the borehole after disturbance by drilling (as indicated in the figure by the cold colors for two months after the deployment). From the observed

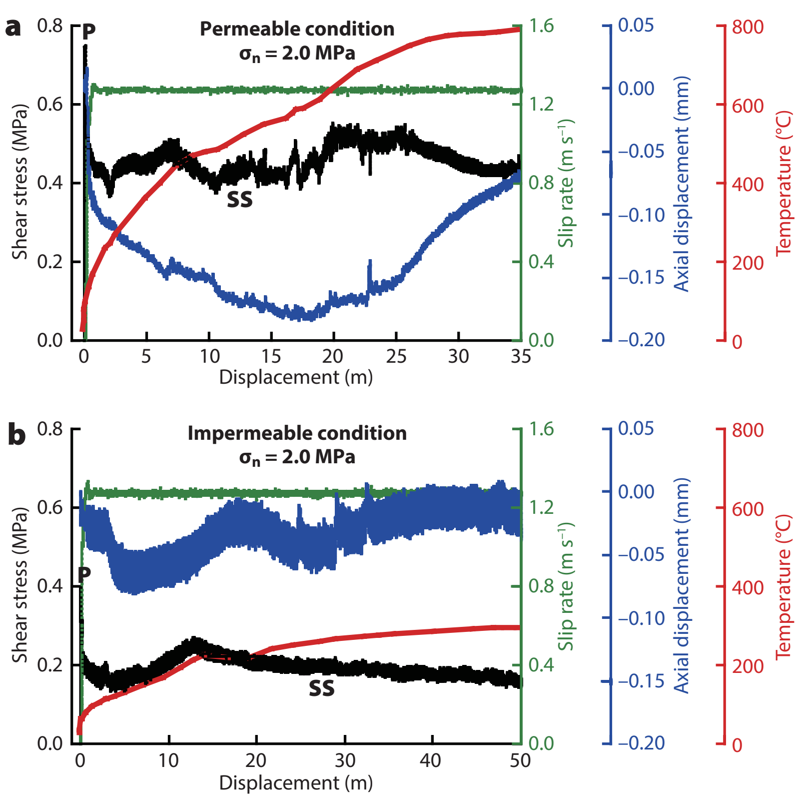


FIGURE 11. Results of high-velocity friction experiment using cores from the plate boundary zone. Shear stress (black line), slip rate (green line), axial displacement (blue line), and temperatures (red line) during the experiment under (a) permeable and (b) impermeable conditions under the normal stress of 2.0 MPa are plotted as a function of displacement. P and SS indicate the initial peak shear stress and the steady-state shear stress (Ujiie et al., 2013).

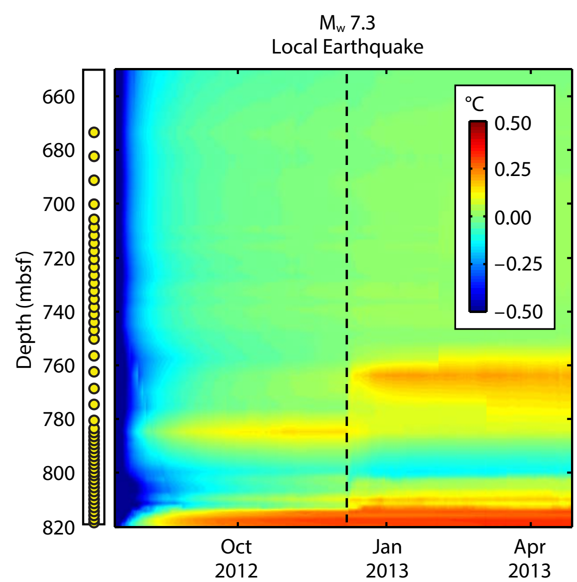


FIGURE 12. Time-depth temperature map in the JFAST borehole. Yellow dots indicate locations of temperature sensors below ~650 mbsf. Colors indicate residual temperatures after the background geotherm is removed. *Adapted from Fulton and Brodsky, 2016*

temperature anomaly of 0.3°C, an average shear stress during the fault slip was estimated to be 0.54 MPa, which corresponds to an apparent frictional coefficient of 0.08. These extremely low values (as compared to standard "Byerlee" rock friction values of 0.65 to 0.8 observed in decades of laboratory experiments at low speed and inferred from small faults globally) are consistent with those estimated by the laboratory experiment described above, in between the permeable and impermeable laboratory results, but closer to the results from the impermeable case (Ujiie et al., 2013). The implication is that the fault slipped with extremely little frictional resistance, akin to the coefficient of friction for a banana peel underfoot (Mabuchi et al., 2012).

These direct measurements, the first of their kind for a major earthquake, contributed greatly to understanding of how rapid, coseismic slip can and does propagate to the seafloor, triggering tsunamis. Taken together with the results from NanTroSEIZE, CRISP, and Sumatra drilling, the discovery of conditional and state-dependent frictional properties of the shallow fault zone revolutionized our understanding of seismic slip in subduction megathrust fault zones. Furthermore, JFAST was the first rapid response IODP expedition of any kind, demonstrating that this approach is feasible and can pay rich rewards.

SYNTHESIS AND CONCLUSIONS

In the IODP era, scientific ocean drilling has permitted rapid advances in the understanding of subduction megathrust properties and processes. It has done so by being the field laboratory, observatory, and data-based ground truth for a wide range of hypotheses based on remote geophysical observations. Over the past three decades, we have seen the advent of broadband seismology and continuous, high-precision geodesy, both on land and now offshore. Borehole observatories have provided key data sets, illuminating interseismic and coseismic processes. Advances in laboratory friction studies and many other types of geological, microstructural, and geochemical measurements have been possible only because of the availability of samples obtained through scientific ocean drilling, and many paradigms have fallen by the wayside as new ones have emerged. The consensus view now is that, rather than faults neatly dividing into seismogenic vs. aseismic, a spectrum of fault behaviors is governed by specific lithology, pore fluid pressure, ambient stress conditions, and propagation of rupture from depth. Observatories are revealing fault processes in real time, permitting tests of new, more sophisticated and nuanced hypotheses on what controls fault locking and release during slow and fast rupture.

Important avenues for future research include understanding the reasons why some megathrust earthquakes do not slip all the way to the surface, as well as understanding what governs locking vs. creeping fault systems. With recent observations suggesting that faults near the tip of a subduction system can be locked, quantifying the spatial extent of and controls on shallow locking has emerged as an urgent question for seafloor geodesy and future drilling, sampling, and observatory installation (see Wallace et al., 2019, in this issue for the first major foray into addressing this topic). Exploring how lithology controls frictional stability and slip behavior, particularly in the marine carbonates that typify deep pelagic sediments in many places, is another high-priority goal.

The factors governing tsunamigenesis remain poorly understood—for example, are faults that do not directly displace the surface capable of creating sufficient seafloor deformation to spawn tsunamis? If so, under what conditions? Studies of the role of large-scale wedge structures in promoting slip on splay faults as a source of tsunamis and submarine slope failure (e.g., Haeussler et al., 2015) will shed light on global geohazards related to tsunamigenic subduction earthquakes.

As this article goes to press, IODP Expedition 358 is conducting riser drilling at Site C0002 in the NanTroSEIZE transect. The expedition's main objective is to deepen the hole to more than 5,000 mbsf by April 2019, thereby sampling the main plate boundary fault zone at the depth of slow slip, tremor, and likely partial locking as well. This hole would complete the NanTroSEIZE transect and set the stage for final deployment of the first real-time megathrust plate boundary observatory inside a deep seafloor borehole.

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