International Ocean Discovery Program
Expedition 362 Scientific Prospectus

The Sumatra Subduction Zone:

The role of input materials in shallow seismogenic slip and forearc plateau development

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Abstract

The 2004 Mw 9.2 earthquake and tsunami that struck North Sumatra and the Andaman-Nicobar Islands devastated coastal communities around the Indian Ocean and was the first earthquake to be analyzed by modern techniques. This earthquake and the Tohoku-Oki Mw 9.0 earthquake and tsunami in 2011 showed unexpectedly shallow megathrust slip. In the case of North Sumatra, this shallow slip was focused beneath a distinctive plateau of the accretionary prism. This intriguing seismogenic behavior and forearc structure are not well explained by existing models or by relationships observed at margins where seismogenic slip typically occurs farther landward. The input materials of the North Sumatran subduction zone are a distinctive, thick (up to 4–5 km) sequence of primarily Bengal-Nicobar Fan–related sediments. This sequence shows strong evidence for induration and dewatering and has probably reached the temperatures required for sediment-strengthening diagenetic reactions prior to accretion. The correspondence between the 2004 rupture location and the overlying prism plateau, as well as evidence for a strengthened input section, suggests the input materials are key to driving the distinctive slip behavior and long-term forearc structure. The aim of Expedition 362 is to begin to understand the nature of seismogenesis in North Sumatra through sampling these input materials and assessing their evolution, en route to understanding such processes on related convergent margins. Properties of the incoming section affect the strength of the wedge interior and base, likely promoting the observed plateau development. In turn, properties of deeper input sediment control décollement position and properties, and hence hold the key to shallow coseismic slip. During Expedition 362, two primary, riserless sites (proposed Sites SUMA-11C and SUMA-12A) will be drilled on the oceanic plate to analyze the properties of the input materials. Coring, downhole pressure and temperature measurements, and wireline logging at these sites will constrain sediment deposition rates, diagenesis, thermal and physical properties, and fluid composition. Postexpedition experimental analyses and numerical models will be employed to investigate the mechanical and frictional behavior of the input section sediments/sedimentary rocks as they thicken, accrete, and become involved in plate boundary slip system and prism development. These samples and downhole measurements will augment the internationally collected site survey bathymetric, seismic, and shallow core data that provide the regional geological framework of the margin.

Schedule for Expedition 362

Expedition 362 is based partly on Integrated Ocean Drilling Program (IODP) drilling Proposals 837-Full and 837-Add (**http://iodp.tamu.edu/scienceops/expeditions/sumatra_seismogenesis.html**). Following ranking by the IODP scientific advisory structure, Expedition 362 was scheduled for the R/V *JOIDES Resolution*, operating under contract with the JOIDES Resolution Science Operator (JRSO). At the time of publication of this *Scientific Prospectus*, the expedition is scheduled to start in Colombo, Sri Lanka, on 6 August 2016 and to end in Singapore on 6 October 2016 (61 total days). Accounting for 5 days of port call and 7 days of transit, a total of 49 days will be available for the coring and logging program described in this report (for the current schedule, see **http://iodp.tamu.edu/scienceops**). Additional details about the facilities aboard the *JOIDES Resolution* can be found at **http://iodp.tamu.edu/labs/ship.html**.

Introduction

On 26 December 2004, a Mw ~9.2 earthquake struck Sumatra and the Andaman-Nicobar Islands (e.g., Park et al., 2005) (Figure **F1**). The resulting tsunami inundated coastal communities around the Indian Ocean, killing more than 290,000 people. The high–moment release, southern 2004 rupture region was centered beneath an unusually wide (~150 km) forearc plateau, representing the surface of the modern accretionary wedge bounded by steep slopes, which contrasts with the wedge structure of many other accretionary margins (Moore et al., 1980; Henstock et al., 2006; Fisher et al., 2007). This earthquake was followed by the Mw 8.7 Nias earthquake in March 2005 (e.g., Hsu et al., 2006; Briggs et al., 2006), and by others in 2007 (e.g., Konca et al., 2008) and 2010 (Newman et al., 2011). These earthquakes all ruptured megathrust sections between the Indo-Australian and Burma-Sunda plates (Figures **F1**, **F2**) and may constitute a repeating series (Sieh et al., 2008). The 2004 and 2005 events were the first great earthquakes to be analyzed using advanced seismological and geodetic techniques and the first of a series of Mw ~9 earthquakes forcing us to reevaluate subduction earthquake models. In 2012, large-magnitude oceanic plate earthquakes ruptured basement west of the 2004 rupture zone (Figure **F3**; Wei et al., 2013; Carton et al., 2014).

Prior to 2004, the Sunda margin structure was characterized generally from earlier surveys including the unusual plateau morphology of the North Sumatran prism (e.g., Moore et al., 1980). Since the 2004 earthquake, many international expeditions have collected data (e.g., Figure **F2A**) that are helping to improve our understanding of the detailed geological framework (e.g., Araki et al., 2006; Fisher et al., 2007; Sibuet et al., 2007; Franke et al., 2008; Singh et al., 2008; Dean et al., 2010; Klingelhoefer et al., 2010; Gulick et al., 2011). The sedimentary succession on the 60–70 Ma basaltic crust of the oceanic plate comprises a basal pelagic layer overlain by the Nicobar submarine fan sequence. This succession may be comparable to some other subduction margins, but here the sediments are thicker, have mostly accumulated gradually (unlike the Cascadia and Alaska margins with large influxes of Quaternary sediment), and are in thermal equilibrium. The Sunda margin is therefore likely to have physical and mechanical properties different from other groundtruthed input sections but of relevance to several other undersampled subduction margins with unknown earthquake records and potential (e.g., the Lesser Antilles and the Makran).

The central aim of Expedition 362 is to begin to understand the nature of seismogenesis in North Sumatra, en route to understanding such processes on related margins. The 2004 earthquake, followed by Tohoku-Oki in 2011, has shown unexpectedly large magnitudes and shallow seismogenic slip (Figure **F4**). This drilling project will collect samples and data required to investigate how input materials drive shallow slip and influence forearc morphology. Our ultimate goal is to understand hazard potential for this margin and eventually others with similar strength behavior and morphology.

Background

Evidence for shallow seismogenic slip

A generally accepted model of subduction zone slip behavior (e.g., Moore and Saffer, 2001) places the thermally and material property–controlled seismogenic zone landward, with the outermost forearc décollement expected to be aseismic in velocity-strengthening unconsolidated materials (Wang and Hu, 2006) (e.g., the Nankai and South Chile margins). Wells et al. (2003) and Song and Simons (2003) propose that megathrust slip is focused beneath the gravity low of a (forearc) basin. However, recent Mw ≥ 9 subduction megathrust earthquakes have challenged these models. The 2011 Tohoku-Oki earthquake showed that rapid and large slip could occur close to or at the trench, and the majority of the (southern) 2004 Sumatra-Andaman earthquake moment release occurred beneath the prism. Despite the range of slip models for the 2004 earthquake, there are significant common features (Figure **F4**): offshore North Sumatra is the location of the greatest seismic moment release (e.g., Ammon et al., 2005); the rupture propagated seaward beneath a large part of the prism offshore North Sumatra (forearc plateau), rather than being focused beneath a gravity low reflecting the sediment-filled forearc basin (models of Wells et al., 2003; Song and Simons, 2003), with some suggestions that slip could extend close to the trench (Henstock et al., 2006; Gulick et al., 2011). Slip during the 2005 Sumatra rupture was different: it was concentrated beneath the forearc islands and not beneath the seaward-tapered prism or the forearc basin. Other margins have experienced ruptures beneath the forearc high similar to the 2005 rupture (e.g., Kamchatka 1952, Alaska 1964, Chile 2010). Clearly, a single rupture model beneath the forearc basin does not fit all margins and may not be typical of the largest ruptures. Drilling the North Sumatran margin, focusing initially on its input materials, will provide an accretionary margin site complementary to drilling at the erosional Japan Trench margin, where extremely weak materials appear to have enabled very shallow and large slip (e.g., Chester et al., 2012). Together, these new drill sites will allow us to investigate the factors controlling shallow seismogenic slip potential at subduction zones globally.

The correspondence between the southern 2004 rupture location and overlying prism plateau suggests a fundamental relationship between material properties, seismogenesis, and long-term evolution of the forearc. Coulomb wedge theory (Davis et al., 1983; Dahlen, 1984) predicts that variations in forearc surface slope reflect changes in basal fault dip or in the balance between the internal wedge strength and shear stress on the plate boundary. Wang and Hu (2006) predict an outer Coulomb wedge and an inner stable region that stores and releases elastic strain; accretion of "strong" input materials might limit the scale of the outer wedge, bringing stable behavior and coseismic slip far seaward.

Inputs to subduction zones and the role of a thick sedimentary input section

The significance of input sediments for development of prism structure and morphology and slip behavior of the décollement in accretionary margins is well known. A number of ocean drilling projects have targeted input sites to address such questions (reviewed by Underwood, 2007). Key parameters for fault development and seismogenesis include clay and silica mineralogy (affecting diagenetic fluid release and frictional properties), hydrogeology (permeability, flow pathways, and pore fluid pressure), and thermal structure. The significance of thick input stratigraphy, where basal sediments are subjected to high temperatures and may be partially lithified, has recently been highlighted, for example at the North Sumatran margin where the input section is 4–5 km thick and includes high-velocity sediments at depth (Dean et al., 2010; Gulick et al., 2011; Geersen et al., 2013) and at the Makran margin where thicknesses reach >7 km (Smith et al., 2012, 2013). At locations where thick sediment sections have accumulated over long time periods and are thus in thermal equilibrium with high temperatures at their base, we might expect the higher degree of diagenesis and lithification to shift the transition from aseismic to seismogenic behavior farther seaward, potentially to the trench. This strengthening effect could, however, be counteracted by high pore fluid pressures (e.g., Davis et al., 1983; Bangs et al., 2004; Saffer and Bekins, 2006). Within a submarine fan succession (including the relatively distal North Sumatran input section), there may be coarse-grained material that has contrasting shear strength, permeability (and hence fluid flow and cementation), and consolidation trends relative to fine-grained materials (e.g., Spinelli et al., 2007). Coarser grained sediments may facilitate dewatering, minimize buildup of pore fluid pressure, and increase induration. Some sections of the North Sumatran input section are highly faulted (Figures **F5**, **F6**, **F7**, **F8**); these faults may act as vertical permeability pathways that enhance the dewatering process. Ultimately, the mechanical and frictional properties of a deeply buried input section are a balance between (1) overpressure generated by consolidation and diagenetic processes and (2) dehydration and induration strengthening the section. In this input section, this balance is likely primarily controlled by permeability and heating.

North Sumatran margin forearc structure

Forearc structure and topography are strongly linked to plate interface seismogenic behavior (e.g., Wang and Hu, 2006), and both in turn reflect input material properties and their evolution. Several structural models that may control or contribute to the distinctive forearc plateau of the North Sumatran prism have been proposed (including a passive roof duplex or bivergent wedge model; Fisher et al., 2007). These models for forearc growth will be influenced by changes in sediment supply to the margin in terms of volume and properties; for example, passive roof duplexes along collisional mountain fronts are associated with thick, lithified foreland basin sequences (Vann et al., 1986). Drilling will provide incoming material properties that make up the forearc and its base, thus allowing models of forearc formation to be tested.

Bengal-Nicobar fan system

Regional initiation of the Bengal Fan is thought to be upper Paleocene–middle Eocene, represented by a regional unconformity and/or lithologic change accompanied by a seismic velocity contrast (Curray and Moore, 1974). The Ninetyeast Ridge (NER) separates the primary Bengal Fan from the Nicobar Fan; the Nicobar Fan, east of the NER, may have initiated slightly later than the Bengal Fan. A late Miocene regional unconformity, linked to changes in collisional and/or intraplate deformation, separates the fan stratigraphy into two units that can be correlated regionally and identified at both fan and NER drill sites (Figure **F9**) (e.g., France-Lanord et al., 2000). An apparently regional Pleistocene unconformity is also identified in seismic data (Curray and Moore, 1982) and in boreholes (e.g., Leg 116 sites in Figure **F9**; Cochran, 1990). Accumulation rates on the fans are probably linked to monsoon intensity and resulting changes in continental run-off. Decreased Bengal Fan accumulation rates after ~7–8 Ma were considered a result of weakening monsoon strength (Burbank et al., 1993) but have been more recently reinterpreted as a function of weakening in seasonal precipitation (Clift et al., 2008). Pliocene accumulation rates at the distal Nicobar Fan (Deep Sea Drilling Project [DSDP] Site 211) are twice those of the equivalent period on the more proximal Bengal Fan (DSDP Site 218; Pimm, 1974), suggesting that sediment flux may have switched from the Bengal to Nicobar Fan, possibly because of large-scale lobe avulsion. Accumulation rates on the Bengal Fan remained relatively low until ~1 Ma, at least in the region of the Leg 116 drill sites (France-Lanord et al., 1993), when sediment supply rates increased significantly, but the NER appears to have blocked late Pleistocene–recent transport of sediments to the Nicobar Fan and Sunda Trench (Curray and Moore, 1974; Moore et al., 1982). Because the submarine fans have prograded southward at DSDP Site 211 at 10°S on the distal Nicobar Fan, the earliest fan deposits are Pliocene in age (von der Borch, Sclater, et al., 1974).

The nature and impact of deformation and climatic changes at 7–8 Ma remain enigmatic, so new drill sites that sample the Nicobar Fan would contribute to our understanding of monsoon initiation and intensification. If the late Miocene–Pliocene history is reduced in the Bengal Fan, then the Nicobar section may prove crucial in deriving a more complete erosional history for the Ganges-Brahmaputra river system. The oldest accreted sediment gravity flows exhumed at the forearc islands are approximately middle Eocene on the Andaman-Nicobar Islands and late Oligocene/early Miocene on Nias (Karig et al., 1980; Curray and Moore, 1974; Karunakaran et al., 1975; France-Lanord et al., 2000), helping to constrain fan system initiation timing. Karig et al. (1980) argue that current prism building started in the late Oligocene. Based on fan history from drill sites and forearc islands, we estimate that at the latitude of the Expedition 362 sites, fan deposition began approximately in the late Eocene to early Oligocene.

Recent drilling of the Bengal Fan (e.g., Expedition 354 [France-Lanord et al., 2015]) is providing new data on fan system history (Figure **F9**); these new results will be incorporated into the Expedition 362 sample analysis strategy and used to help direct postcruise research as they become available.

North Sumatran input stratigraphy

The North Sumatran input section is divided into two primary sections separated by an unconformity with two units below and one unit above the unconformity:

- Unit 1: A seaward-thinning trench wedge of Nicobar Fan sediments and locally derived, interbedded hemipelagic and sediment gravity-flow deposits (up to 3 km thick at the deformation front) controlled by lower plate flexure, seismically characterized by high-amplitude continuous reflectors. This unit is separated from Unit 2 by an unconformity.
- Unit 2: A Nicobar Fan section of interbedded hemipelagic-pelagic and gravity-flow (including turbiditic) sediments, seismically characterized by high-amplitude continuous reflectors. This unit is expected to include the regional 7–8 Ma disconformity/unconformity. This unit includes the shallower of the two horizons proposed to develop into the décollement (Cook et al., 2014).
- Unit 3: A lower pelagic section, equivalent to the sediments sampled on the NER (nannofossil ooze, clay, chalk, and chert), seismically characterized by increased acoustic transparency. This unit includes the deeper of the two horizons proposed to develop into the décollement (Dean et al., 2010). This potential pre-décollement horizon is estimated to be a relatively weak, high-porosity, and fluid-rich layer indicated by a high-amplitude, negative polarity seismic reflector located ~500 m above basaltic basement.

In addition to the sedimentary units, Expedition 362 will also sample the Unit 3/basement interface and 10 m of basaltic basement.

Site survey data

For the two primary sites, a limited network of seismic profiles is available, including crossing lines, showing the 3-D basement and stratigraphic structure and faulting. The primary seismic lines were acquired by the Federal Institute for Geosciences and Natural Resources (BGR; Germany) research Cruise SO-186-2 as part of the SeaCause program (Figures **F5**, **F6, F7, F8**). The data are jointly owned by German and Indonesian institutions. Additional regional and crossing profiles were collected by the National Center for Scientific Research (CNRS; France) MD116 cruise and Western Geco (Singh et al., 2010). For primary Site SUMA-11C, a crossing line exactly at the site is not available, but the regional structural context is provided by local crossing profiles (Figure **F2B**). Seismic velocity data for depth conversions were compiled from refraction- and wide-angle reflection–derived velocities (Bull and Scrutton, 1990b; Radhakrishna et al., 2010) and multichannel seismic–derived velocity information from a number of seismic reflection data sets (e.g., Dean et al., 2010; Singh et al., 2010). The Bull and Scrutton (1990b) velocity profile and data from Singh et al. (2010) and Dean et al. (2010) were used for depth estimate calculations for the two primary drill sites and for contingency sites. Multibeam bathymetry data are available for the entire incoming oceanic plate region relevant to these sites and for the majority of the marine forearc of the subduction zone offshore Sumatra. Regional heat flow data across the incoming Indo-Australian oceanic plate are available from Vacquier and Taylor (1966). Piston core data from *Roger Revelle* Cruise 0705 "PaleoQuakes07" (including core images and physical property data) provide indications of likely lithologies and sedimentation rates from the recent sedimentary record.

All supporting site survey data for Expedition 362 are archived at the **IODP Site Survey Data Bank** (select P837 for the proposal number).

Scientific objectives

The primary objectives of Expedition 362 are to establish (1) the initial and evolving properties of the North Sumatran incoming sedimentary section and (2) the potential effect of these properties on seismogenesis, tsunamigenesis, and forearc development for comparison with global examples. To address these objectives, two riserless drill sites (proposed Sites SUMA-11C and SUMA-12A) will sample and log the oceanic plate input succession of the southern 2004 earthquake rupture zone, including the distal part of the trench wedge, the Nicobar Fan succession, the prefan pelagic succession, and the sediment/basaltic basement interface. The two primary sites will sample the sediment/basement interface and oceanic crustal basalt at two different locations, offering potentially different hydrogeological conditions. Site SUMA-11C has thinner Units 2 and 3 providing less sedimentary section to basement, which provides increased opportunity to access the pelagic section, including one of the potential décollement surfaces (Dean et al., 2010), and to sample basaltic basement. The sites will be used for sampling stratigraphic, chemical, physical, thermal, biological, and structural elements to analyze how the sediments and diagenetic processes evolve before and during accretion. Postexpedition experimental and modeling methods will be used to extrapolate input properties to greater stresses and temperatures due to burial and subduction through time. We anticipate these processes create a strong prism core and promote shallow seismogenic slip.

Primary objectives

1. *To determine the lithology, sedimentation rates, and physical properties of the input section and to determine marked changes in sedimentation rate and lithology with time that would influence physical properties of the section.*

By drilling and sampling Units 2 and 3 and the distal part of Unit 1 (proposed Sites SUMA-11C and SUMA-12A; Figures **F5**, **F6**, **F7**, **F8**), we will calculate sediment accumulation rates, characterize the proportion and distribution of coarse- versus fine-grained lithologies, and compare with data from other Bengal Fan boreholes. These regional boreholes will also allow us to relate local changes to regional tectonics and climate or more local switching of sediment supply between the fan systems. Standard chronological methods such as magnetic reversals, radiolarians, and diatoms will be used to develop the chronostratigraphy, and calcareous microfossils should also be preserved in deeper/older parts of the section at proposed Sites SUMA-11C and SUMA-12A. Within the succession we expect to sample (1) late Miocene sediments, specifically the critical 7–8 Ma timing of major deformational and climatic change recorded in other parts of the Indian Ocean, Asia, and the Himalayan-Tibetan system but less well in the Bengal Fan; (2) Pliocene sediments, a time when distal Nicobar Fan deposition (DSDP Site 211) exceeds more proximal Bengal Fan sedimentation (DSDP Site 218); and (3) Pleistocene sediments, to test for increase (regional trend) or decrease (Nicobar Fan trend) in sediment flux. Only the distal thin part of the trench wedge (Unit 1) will be sampled at the sites, but from age information at both primary sites and from shallow piston cores we should be able to extrapolate and estimate sedimentation rates within the full trench wedge closer to the subduction zone. Changes in accumulation rate and lithology impact the growth of the prism through time and the physical properties of the prism interior and base, with the latter influencing décollement properties. Variability in physical, chemical, and thermal properties of the section will be determined by integrating core, log, and downhole tool data.

2. *To assess whether the deep sampled input sediments that eventually will form the interior and base of the accretionary prism and develop into the décollement fault are indurated, dense, compacted, predominantly dewatered, and becoming diagenetically altered. These effects will magnify as the input section thickens and is accreted. Strengthening of the sedimentary section would contribute to a strong prism core and promote shallow seismogenic slip.*

We will test for evidence of induration, dewatering, compaction, and thermal properties of sediments sampled in the lowermost input section (proposed Sites SUMA-11C and SUMA-12A). Standard measurements (lithology, mineralogy, fluid chemistry, and petrophysical properties) will be augmented with downhole pressure and temperature measurements. Through core-log-seismic integration and experimental and modeling techniques we will predict the effects of thickening of the input section from the drilled sites to the trench wedge and deformation front, including dewatering profile development. Further predictions using postexpedition experimental and numerical analyses will include evaluation of the effects of enhanced diagenesis under higher pressure-temperature (P-T) conditions at depth. These analyses will potentially be integrated with data from exhumed prism samples or other exhumed sedimentary sections with analogous lithologic and burial history properties. Rapid dewatering at relatively shallow depths may be supported by sediments rich in silt/sand (thin Nicobar Fan gravity-flow deposits) and amplified by faulting that extends from basement to the seafloor in places. Pore fluid and vein chemistry will be analyzed to further understand the presubduction hydrological system, to assess the state of diagenetic reactions, and to determine the composition of fluids entering the décollement and accretionary wedge system.

3. *To determine the similarities and any distinct differences in lithology and physical properties within the stratigraphic section. In particular between (a) the gradually deposited Unit 2, comprising Nicobar Fan sediments, and (b) the more slowly accumulating pelagic sediments of Unit 3.*

We will sample, log, and compare lithologic, physical, chemical, and thermal properties (including thermal gradient, pore pressure profile, fluid content, and chemistry) of Units 2 and 3 and the top of basaltic basement. In addition, we will sample the distal part of Unit 1 (comprising Bengal-Nicobar Fan and forearc–derived sediment and potentially NER-derived materials), which, at the trench, is very rapidly deposited and therefore contrasts further with Units 2 and 3. Any lithologic and property contrasts are expected to intensify with depth and accretion, which can also be tested through post-expedition experimental studies. Strong contrasts downsection or weak intervals (layers or boundaries) may promote midsection décollement development resulting in duplexing in the prism (e.g., Fisher et al., 2007) and will play an important role in where the basal décollement initiates (within Unit 3 or basal Unit 2; Dean et al., 2010; Cook et al., 2014). The structure of regularly spaced anticlines across the plateau implies a two-tiered system separated by a detachment, with an upper folded layer and deeper sequence that imbricates beneath the roof thrust to form a duplex; this system could be indicative of an incoming mechanical stratigraphy that is two-tiered. Biological factors, including bioturbation and total organic carbon, that may affect sediment mechanical properties will also be analyzed.

Secondary objectives

1. *State of stress in the oceanic plate*

Deformation of the Indo-Australian plate in response to India-Eurasia collision and subduction is an ongoing topic of discussion (e.g., Bull and Scrutton, 1990a; Sager et al., 2013; Deplus et al., 1998; Delescluse et al., 2012), renewed after the unexpectedly large intraoceanic plate earthquakes in 2012 (e.g., Meng et al., 2012; Wei et al., 2013). Many small displacement faults cut the sedimentary section of the oceanic plate with some visible at the seafloor and some offsetting basement (e.g., Figure **F5**) (Geersen et al., 2015), and there is ongoing reactivation of oceanic fracture zones in primarily strike-slip earthquakes (Figure **F3**). The April 2012 earthquakes (including Mw 8.6) ruptured a complex set of faults in close proximity to the Expedition 362 drill sites and may have ruptured the entire lithosphere (e.g., Meng et al., 2012; Wei et al., 2013; Carton et al., 2014). Gathering in situ stress orientations during Expedition 362 drilling and comparing with existing geological and seismological data will improve our understanding of the present-day stress regime and should allow us to analyze the interplay between intraplate and subduction deformation.

We propose to use wireline log data to measure stress orientation where borehole breakouts (the elongation of the borehole parallel to the minimum horizontal stress) exist and can be measured (Zoback, 2007). Wireline Formation MicroScanner (FMS) resistivity images of breakouts and/or drilling-induced tensile fractures

(DITF), combined with FMS azimuthal caliper data to record elongated borehole orientation, can be used to derive stress orientations (e.g., Lin et al., 2010). In addition, acoustic images obtained with the Ultrasonic Borehole Imager (UBI) will provide 360° coverage of the borehole wall to complement the partial FMS coverage. A stress regime related to convergence or extensional flexure (e.g., distinguishing maximum horizontal stress perpendicular to the deformation front or parallel to the convergence direction) can be differentiated from regional collision-related deformation or reactivation of the north-south–trending fracture zones or more complex transtensional deformation with contrasting stress orientations. Drilling at two locations on the oceanic plate between the NER and the subduction zone will offer the potential to evaluate how the stress field changes.

2. *Eastern Indian Ocean records of paleoclimate and regional tectonics*

The proposed drill sites will provide a complete section of the Neogene Nicobar Fan, part of the wider Bengal-Nicobar fan system, indicating onset of sedimentation and changing sedimentation patterns through time. Evidence for major tectonic and climatic change at ~7–8 Ma is currently unresolved in the Bengal-Nicobar fan system, with existing sites suggesting that significant sediment flux may have passed from the Bengal to Nicobar Fan during (at least) the Pliocene (DSDP Site 211 versus Site 218), but with only the most distal Nicobar Fan sampled to date. Our drilling combined with the expanding regional fan drill site data set will demonstrate whether changing sediment flux to specific parts of the Bengal Fan system reflects switching of fan lobes or a truly regional change in sediment supply to the deep basin. This has important implications for how onshore erosional processes have responded to changes in monsoonal strength at this time and influenced changes in sediment supply to the accretionary Sunda margin. A variety of provenance, thermochronology, and chemical weathering proxies (e.g., Najman et al., 2012) will be applied to the distal gravity-flow deposit record in order to reconstruct changing continental environmental conditions, as well as changing sources of sediment to the Indian Ocean during the exhumation of the Greater and Lesser Himalaya during the early and late Miocene, respectively. The sites drilled during this expedition will complement existing sites (Figure **F9**) and recently drilled sites in the region such as those drilled during Expeditions 353, 354, and 355 tackling Himalayan/Tibetan collisional and uplift history and monsoon development.

Operations plan

Drilling and coring strategy

The operations plan and time estimates for proposed primary Sites SUMA-11C and SUMA-12A are presented in Table **T1**. Alternate sites and contingency operations are presented in Table **T2**. There has been no previous drilling on the Sunda margin. The time estimates used are based on anticipated formation lithologies, depths inferred from seismic interpretations, and previous experience at similar settings.

The drilling strategy is to begin by drilling at proposed Site SUMA-11C, followed by drilling at proposed Site SUMA-12A. Proposed Site SUMA-12A will target stratigraphy similar to that found at proposed Site SUMA-11C but with a slightly thicker sedimentary section.

Hole A will be cored with the advanced piston corer (APC)/extended core barrel (XCB) coring systems (**http://iodp.tamu.edu/tools**) to ~800 meters below seafloor (mbsf) at Site SUMA-11C and to ~650 mbsf at Site SUMA-12A. APC cores will be oriented with the Icefield MI-5 Digital Borehole Survey Tool (**http://iodp.tamu.edu/tools/logging**). APC cores will be taken with nonmagnetic core barrels. After completing coring in Hole A at Site SUMA-11C, the hole will be conditioned, displaced with logging mud, and logged as per the logging plan (see **Downhole logging**, this section).

Hole B at each site will start with casing operations. A reentry cone with a single casing string will be installed using the drill-in method. This strategy is designed to maximize our success at sampling the complete stratigraphic section at each site. Rotary core barrel (RCB) coring will extend from the bottom of the casing to the target depth (~1450 mbsf plus 10 m of basement at proposed Site SUMA-11C and ~1600 mbsf plus 10 m of basement at proposed Site SUMA-12A). RCB cores will be taken with nonmagnetic core barrels. After completing coring in Hole B at both sites, the holes will be conditioned, displaced with logging mud, and logged as per the downhole logging plan.

Formation temperature and pressure

We propose to take measurements of downhole formation temperature and pore pressure (Long et al., 2008) to (1) assess the thermal structure and geothermal gradient and infer thermal properties (in conjunction with core measurements) of the input sediment section and (2) provide pore pressure measurements to improve calibration of seismically derived parameters.

We plan a total of 16 deployments using the advanced piston corer temperature tool (APCT-3), Sediment Temperature Tool (SET), sediment temperature/pressure tool (SETP) (see **http://iodp.tamu.edu/tools/logging**), and temperature dual-pressure tool (T2P) (Long et al., 2008) to measure formation temperature and pressure. The T2P, and possibly the SETP, will be deployed with the Motion Decoupled Hydraulic Delivery System (MDHDS) (Flemings et al., 2013) to reduce heave effects and to improve reliability of measurements. Deployments will be made in Hole A at each site because probe penetration is limited by sediment stiffness, and sediments that require RCB coring will be too stiff for the temperature and pressure tools. We plan to use these data to extrapolate measurements (in particular temperatures) to the base of each borehole.

Downhole logging

The downhole logging plan for Expedition 362 aims to provide continuous stratigraphic coverage of in situ formation properties at proposed Sites SUMA-11C and SUMA-12A. Three tool string configurations are planned for each site, but the logging program may be modified depending on hole conditions and available time. Details of the logging tools are available at **http://iodp.tamu.edu/tools/logging**.

The triple combination (triple combo) tool string measures density, neutron porosity, resistivity, and natural gamma radiation (NGR), along with borehole diameter (caliper log). The UBI will be used as a bottom tool with the triple combo. The caliper log provided by the density tool will allow an assessment of hole conditions and the potential for success of subsequent logging runs. NGR data gathered by the triple combo may prove useful for correlation with NGR measurements collected from the cores on the ship.

The Formation MicroScanner (FMS)-sonic tool string measures NGR, sonic velocity, and oriented high-resolution electrical resistivity images, along with borehole diameter. The NGR data will be used to depth-match the different logging runs. The compressional velocity logs can be combined with the density logs to generate synthetic seismograms for detailed seismic-log correlations.

A third run in Hole B at each site will consist of a check shot survey with the Versatile Seismic Imager (VSI), which is used to acquire a zero-offset vertical seismic profile (VSP). The objective is to establish a direct link between lithostratigraphic depths in the borehole and reflectors in the seismic profiles. The seismic source for the check shots will be a generator-injector air gun, and its deployment is subject to the IODP marine mammal policy; the check shot survey would have to be postponed or canceled if policy conditions are not met.

Risks and contingency plans

Risks

There are a number of risks to achieving the objectives of this program.

Hole conditions

The expected stratigraphy in both sites may include interbedded sands, which may prove difficult to recover; however, sand will likely be a minor component, as documented at other Bengal fan drill sites and from piston coring in the Sunda Trench (e.g., Patton et al., 2013). In addition, deep drilling has been successful at other Bengal Fan sites. Poor hole conditions will be dealt with by using frequent high-viscosity mud sweeps and/or heavy mud to condition the holes. To improve hole stability for deep drilling, the operations plan at both sites is to case off the upper portion of the deep holes (Hole B at each site).

Hydrocarbons and overpressure

The proposed sites have ≥1.4 km sediment cover. However, no indications of hydrocarbons are observed in seismic data or from earlier fan drilling. All sites are in simple oceanic plate basin settings, and there is no evidence of closure from mapping basement and fault structures around the sites on available profiles or of trapped fluids. Sites have been selected to avoid faulting of the sedimentary section. At Ocean Drilling Program (ODP) Leg 116 sites (e.g., Site 717, drilling to 800 mbsf, total section up to 2.4 km; Cochran, Stow, et al., 1989), minimal/no hydrocarbon gases were recorded, total organic carbon is relatively low, kerogen is primarily terrestrial source Type III (and hence gas prone), and organic matter is immature with respect to hydrocarbon generation. Based on the inferred conductive heat flow regime and the thick but gradually deposited sedimentary successions, we do not anticipate pressure-related problems with drilling. This is consistent with previous drilling, but in addition our downhole temperature and pressure measurements will allow parameters and risks to be evaluated during drilling.

Sea state

From August to October the sea state is influenced by a swell coming from Antarctica, but this is not expected to impact operations.

Contingency plans

Two alternate sites (SUMA-11B and SUMA-16A) and optional operations have been identified to provide viable contingency options (Table **T2**) if extra time is available after completion of proposed Site SUMA-11C and SUMA-12A operations. The options presented are not in priority order.

- Drill additional holes for spot coring in zones of interest or poor recovery and/or additional temperature/pressure probe measurements.
- Conduct additional logging runs.
- Select an alternate site for additional stress field measurements. Note that stress field measurements from logging could be obtained without drilling to basement.
- Use a drill string packer (e.g. Shipboard Scientific Party, 1992) to isolate and test the sedimentary section and/or basement. Data could be used to estimate hydrologic properties and stress magnitudes.

Sample and data sharing strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations Policy and Implementation Guidelines posted at **http://www.iodp.org/program-documents**. This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of the Co-Chief Scientists, Staff Scientist, and IODP Curator on shore or curatorial representative on board ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard sampling.

Scientists are expected to submit data and sample requests using the Sample and Data Request Database (**http://iodp.tamu.edu/curation/samples.html**) several months before the beginning of the expedition. Based on shipboard and shore-based research plans submitted by this deadline, the SAC will prepare a tentative sampling plan, which will be revised on the ship as dictated by recovery and cruise objectives. When appropriate (e.g., whole-round samples), the SAC may suggest collaboration and sharing of sample material to maximize the science return on all collected materials. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. The SAC must approve modifications of the sampling strategy during the expedition.

The permanent archive will be the standard archive half of each core. All sample frequencies and sizes must be justified on a scientific basis and will depend on core recovery, the full spectrum of sample requests, and the cruise objectives. Some redundancy of measurements is unavoidable, but minimizing the duplication of measurements among the shipboard scientists and identified shore-based collaborators will be a factor in evaluating data and sample requests.

If some critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. These intervals may require special handling, a higher sampling density, reduced sample size, or continuous core sampling by a single investigator. A sampling plan coordinated by the SAC may be required before critical intervals are sampled.

Postexpedition research

Focused postexpedition research projects are an integral component of the Expedition 362 research program. Integration of laboratory data and numerical model results will provide the ability to extrapolate input properties to greater stresses and temperatures due to burial and subduction through time (e.g., Ask and Morgan, 2010; Karig, 1993; Long et al., 2011; Morgan et al., 2007; Saffer and Tobin, 2011; Spinelli et al., 2007; Stigall and Dugan, 2010; Tobin and Saffer, 2009). Our direct measurements will thus be extended greatly but also can be tested or compared to geophysical data. We will develop methods for taking lithology, composition (detrital and authigenic components, as well as fluids), in situ stress, and physical and thermal properties from drilling to extrapolate sediment-rock chemical and physical properties to depth (increased pressure, temperature, stress, and burial time) within the input section to estimate material properties at the base of section in the trench prior to accretion and to predict mechanical and frictional behavior of the materials on accretion (in the wedge interior and at the plate boundary). Using input lithologies, thermal data, likely fluid composition, and burial history, we can model the evolution of rock properties in space and time (e.g., Lander and Walderhaug, 1999; Makowitz et al., 2006, 2010). Laboratory experiments will be geotechnical in nature, and, where possible, coupled with petrophysical data. Primary experimental approaches will be to document consolidation, permeability, and strength behavior of dominant lithologies under different loading conditions, providing a baseline for forward modeling of active fluid flow, deformation, and evolution of mechanical properties. Modeling techniques will include forward modeling of heat transport, deformation and compaction, and reactive transport. Analysis of exhumed accreted samples or of other similar lithology sections with analogous burial histories can also be used to ground truth and to validate forward modeling techniques and results.

Expedition scientists and scientific participants

The current list of participants for Expedition 362 can be found at: **http://iodp.tamu.edu/scienceops/expeditions/sumatra_seismogenesis.html**.

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Table T1. Primary sites and operations plan, Expedition 362. mbrf = meters below rig floor. EPSP = Environmental Protection and Safety Panel.

Proposed site	Location (latitude, longitude)	Seafloor depth (mbrf)	Operations	Transit (days)	Drilling, coring (days)	Logging (days)
Colombo, Sri Lanka			Begin expedition 5.0	Port call days		
			Transit ~785 nmi to SUMA-11C at 10.5 kt	3.1		
SUMA-11C	3°2.04'N	4180	Hole A - APC/XCB to 800 mbsf with orientation and APCT-3, SETP/T2P measurements;	0	7.8	0
	91°36.35'E		log with triple combo-UBI and FMS-Sonic	0	0	1.4
Depth approved by EPSP to basement + 10 m (1460 m)			Hole B - Reentry system: drill in 10.75" casing with HRT system to 500 mbsf;	0	3.1	0.0
			RCB to 1460 mbsf; log with triple combo, FMS-sonic, and VSI	0	10.9	2.1
			Subtotal days on site: 25.2			
			Transit ~19 nmi to SUMA-12A at 10.5 kt	0.1		
SUMA-12A	2° 45.29' N	4211	Hole A - APC/XCB to 650 mbsf with orientation and APCT-3, SETP/T2P measurements	0	6.0	0.0
	91° 45.58' E		Hole B - Reentry system: drill in 10.75" casing with HRT system to 640 mbsf	0	3.4	0.0
Depth approved by EPSP to basement + 10 m (1610 m)			Hole B - RCB to 1610 mbsf; log with triple combo, FMS-Sonic, and VSI	0	11.7	2.0
			Subtotal days on site: 23.1			
			Transit ~934 nmi to Singapore at 10.5 kt	3.8		
Singapore			End expedition	7.0	42.9	5.4

Port call:	5.0	Total operating days:	55.3
Subtotal on site:	48.3	Total expedition:	60.3

Table T2. Alternate sites and time estimates, Expedition 362. mbrf = meters below rig floor. EPSP = Environmental Protection and Safety Panel.

Proposed site	Location (latitude, longitude)	Seafloor depth (mbrf)	Operations	Drilling, coring (days)	Logging (days)
SUMA-11B	3°5.7323'N	4177	Hole A - APC/XCB to 800 mbsf; APCT-3, SET-P measurements to 600 mbsf; log to 800 mbsf	8.0	1.4
Depth approved by EPSP to basement + 10 m (1610 m)	91°40.0758'E		Hole B - Reentry system; RCB to 1610 mbsf; log with triple combo-UBI, FMS-Sonic, and VSI	17.7	2.0
			Subtotal Days On Site: 29.1		
SUMA-16A	2° 48.9647' N	4210	Hole A - APC/XCB to 800 mbsf; APCT-3, SETP/T2P measurements; log with triple combo-UBI, FMS-Sonic	8.0	1.4
Depth approved by EPSP to basement + 10 m (1620 m)	91° 51.2938' E		Hole B - Reentry system to 800 mbsf; RCB to 1620 mbsf; log with triple combo-UBI, FMS-Sonic, VSI	16.2	2.0
			Subtotal Days On Site: 27.6		

Figure F1. Tectonic setting of Sumatran subduction zone showing major recent and historic plate boundary earthquake ruptures (from Meltzner et al., 2012; rupture areas from that paper and references therein). Black lines = faults, gray lines = fracture zones.

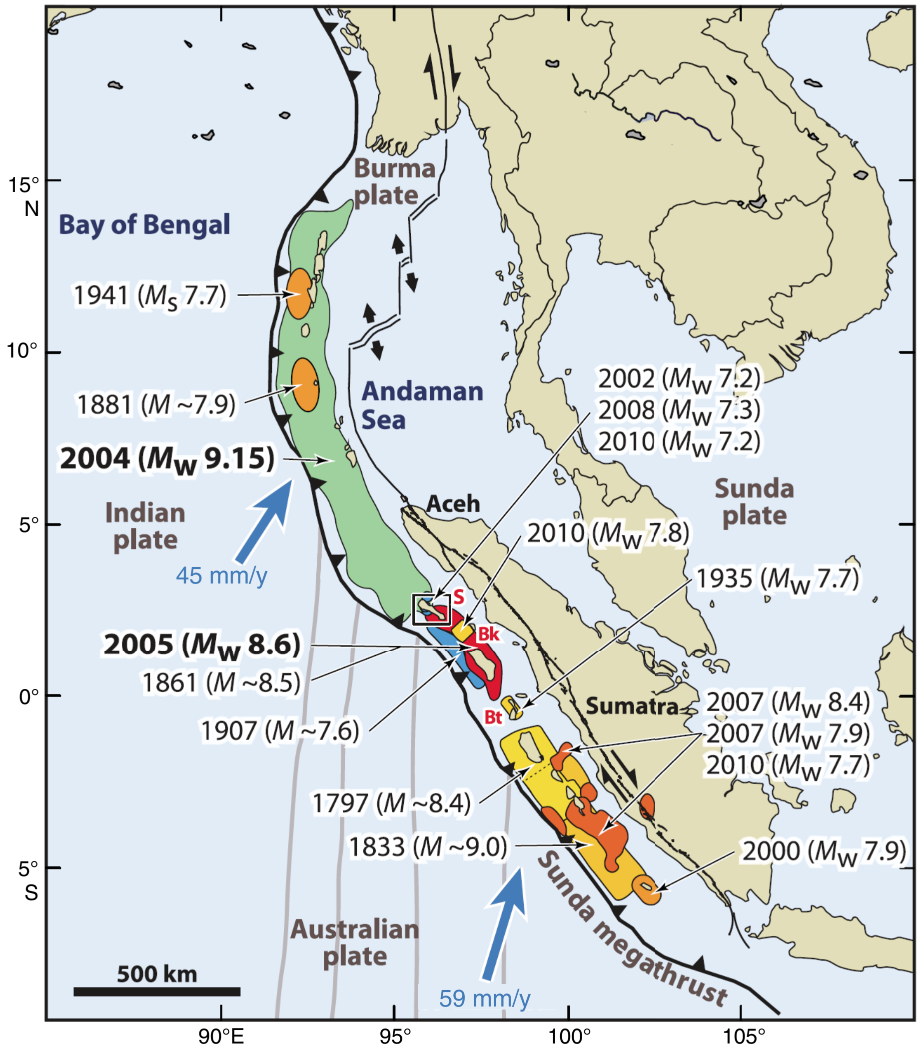


Figure F2. A. Recently collected multichannel seismic reflection profiles across the North Sumatran forearc and southern 2004 earthquake rupture zone and existing earlier profiles overlain on multibeam bathymetry. All primary (large red circles) and alternate (small red circles) drill sites are shown. Insert shows seismicity and focal mechanisms associated with the December 2004 earthquake rupture. (Continued on next page.)

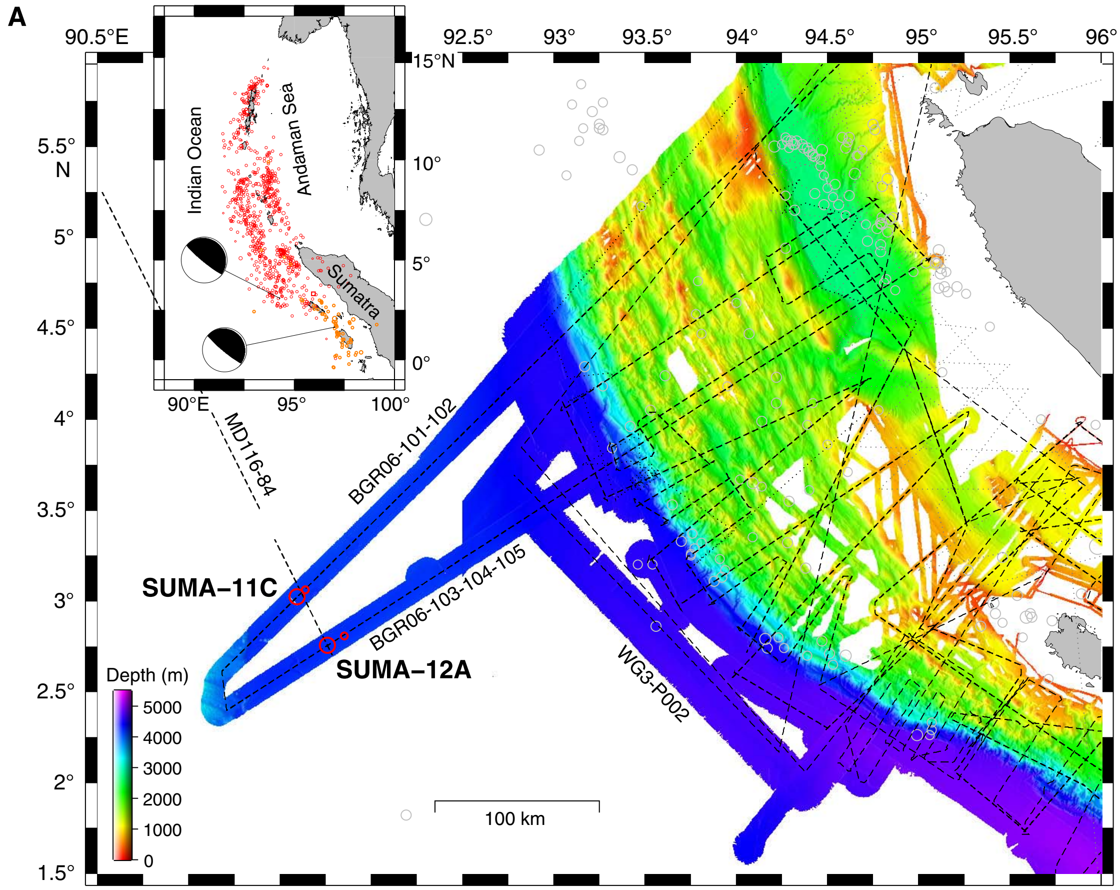


Figure F2 (continued). B. Details of study area showing common depth point (CDP) information along primary seismic profiles and all site locations (primary [large red circles] and alternate [small red circles]).

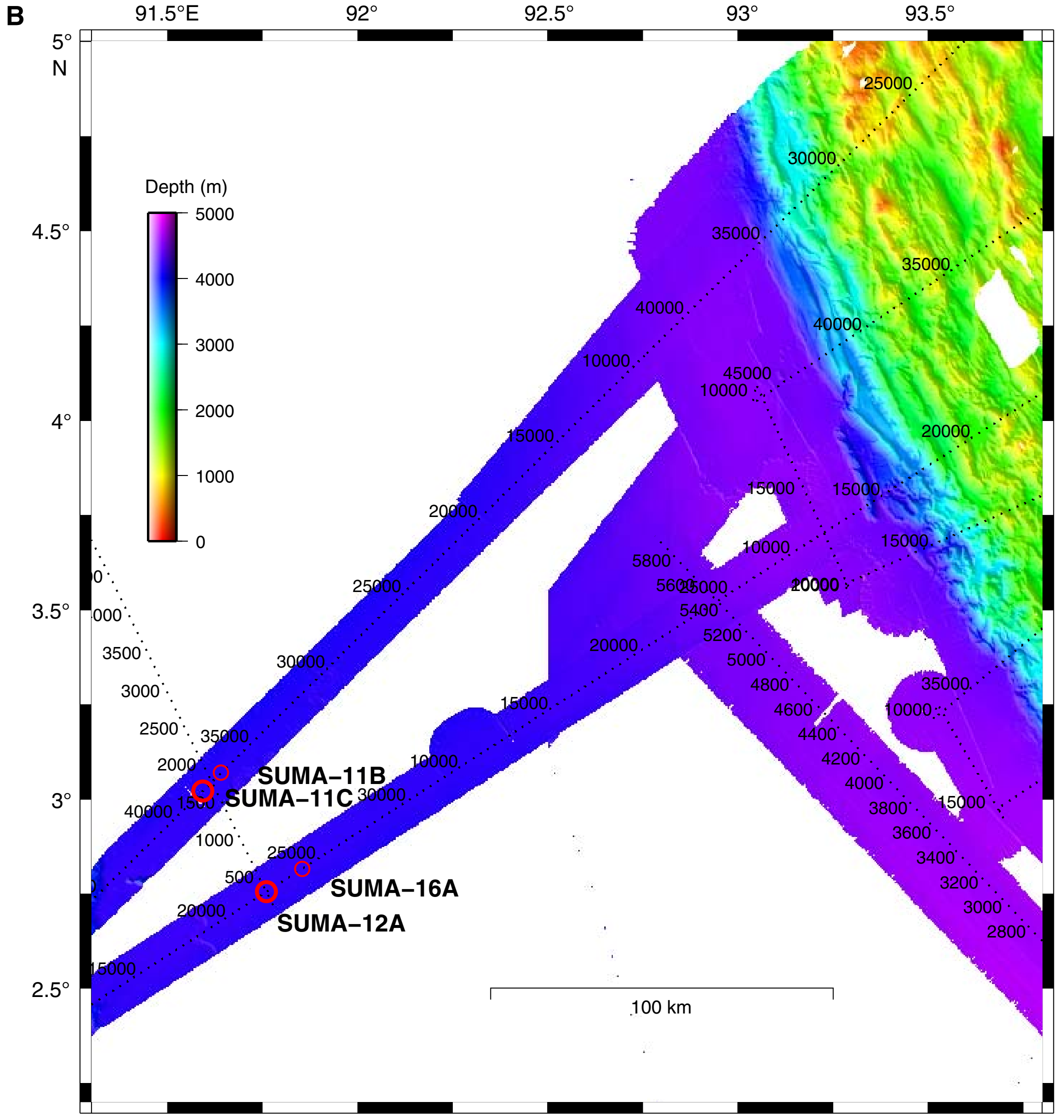


Figure F3. Oceanic plate structure, including fracture zones, of the Wharton Basin and seismicity and focal mechanisms associated with the April 2012 earthquakes (mainshocks [stars] and aftershocks). (From Carton et al., 2014.)

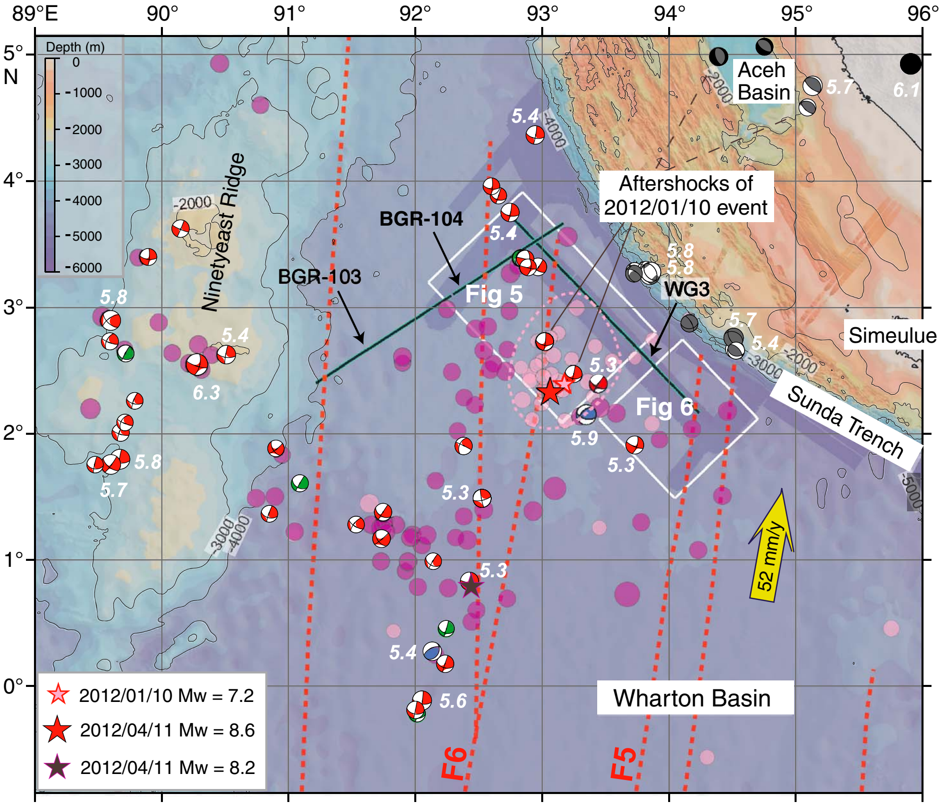


Figure F4. Coseismic rupture models of the 2004 earthquake. Models using seismic and geodetic data: Chlieh et al. (2007) shows coseismic and ~30 day postseismic slip, with slip offshore North Sumatra concentrated beneath the forearc high. Contours = depth of subducting plate. Rhie et al. (2007) shows waveform and GPS inversion suggesting substantial shallow slip (although postseismic transients may be included). Model based on tsunami observations: Fujii and Satake, (2007) shows significant slip on shallow plate boundary.

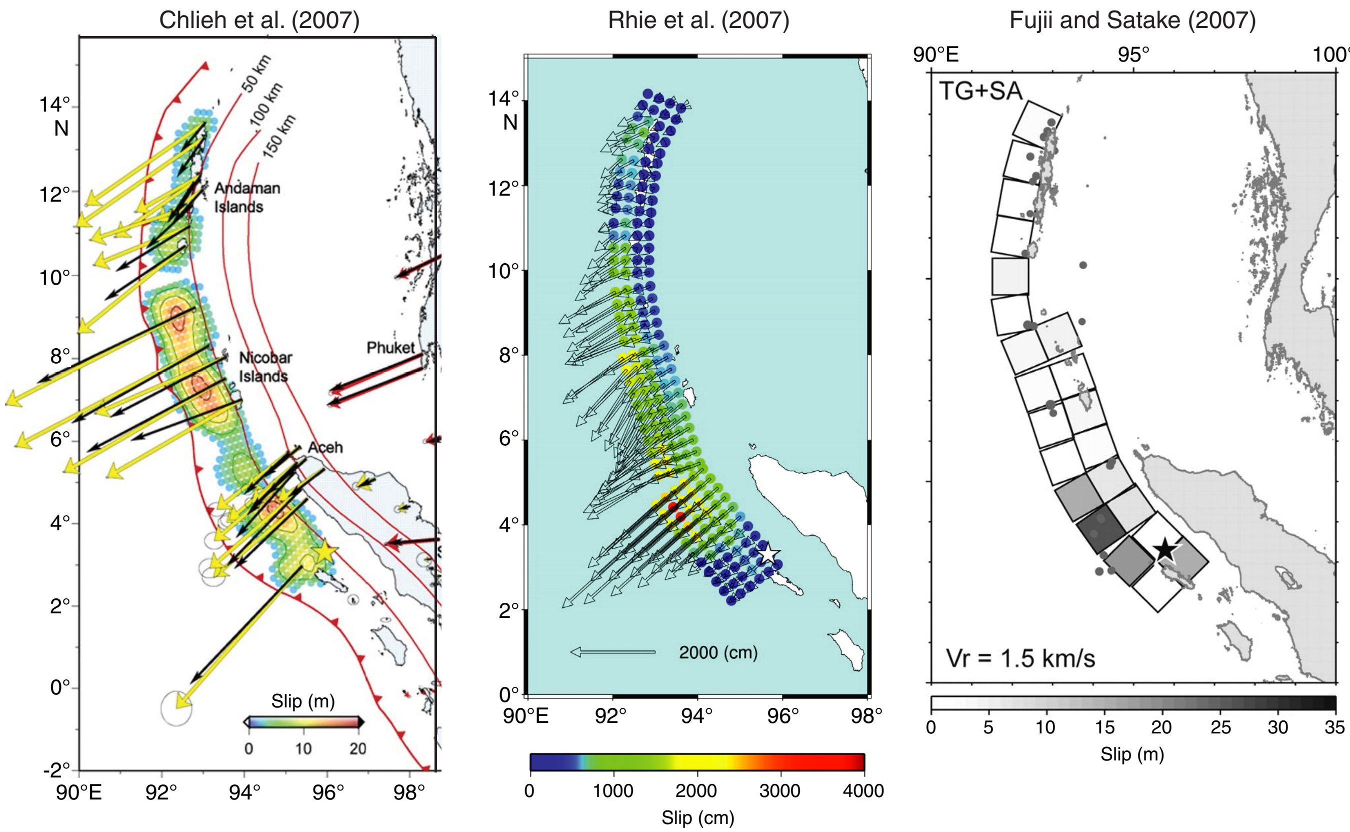


Figure F5. Seismic Profiles BGR06-101 and BGR06-102 across the oceanic plate west of the Sunda subduction zone, North Sumatra from the Ninetyeast Ridge to the deformation front. Blue line = boundary between the trench wedge (Unit 1) and the fan and prefan units (Units 2 and 3, respectively). Green line = interpreted base of fan and top of pelagic sequence (Unit 2/3 boundary). Proposed primary Site SUMA-11C is shown. See Figure **F2** for line locations.

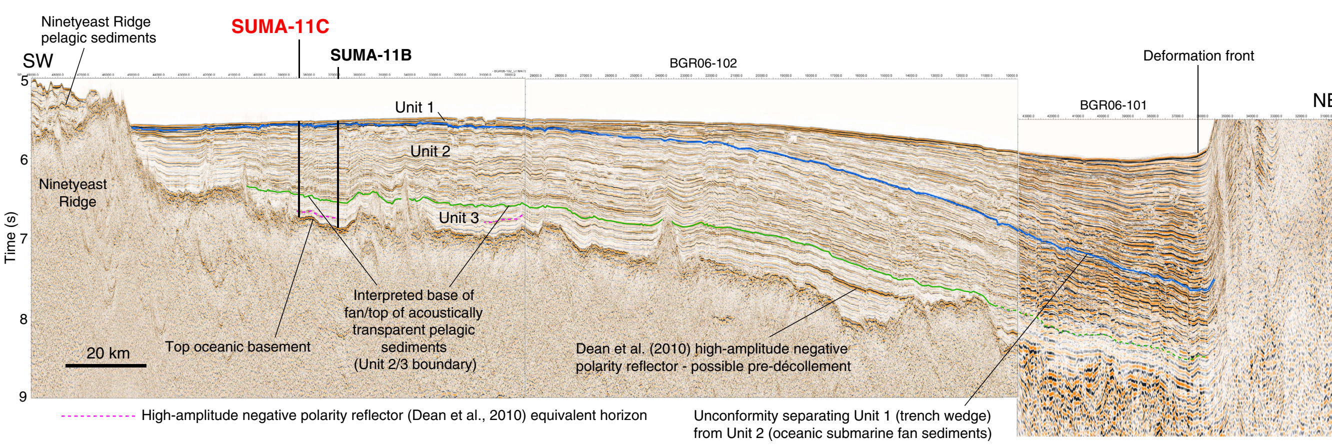


Figure F6. Seismic Profiles BGR06-103, BGR06-104, and BGR06-105 across the oceanic plate west of the Sunda subduction zone, North Sumatra from the Ninetyeast Ridge to the deformation front. Blue line = boundary between the trench wedge (Unit 1) and the fan and prefan units (Units 2 and 3, respectively). Green line = interpreted base of fan and top of pelagic sequence (Unit 2/3 boundary). Proposed primary Site SUMA-12A is shown. See Figure **F2** for line locations.

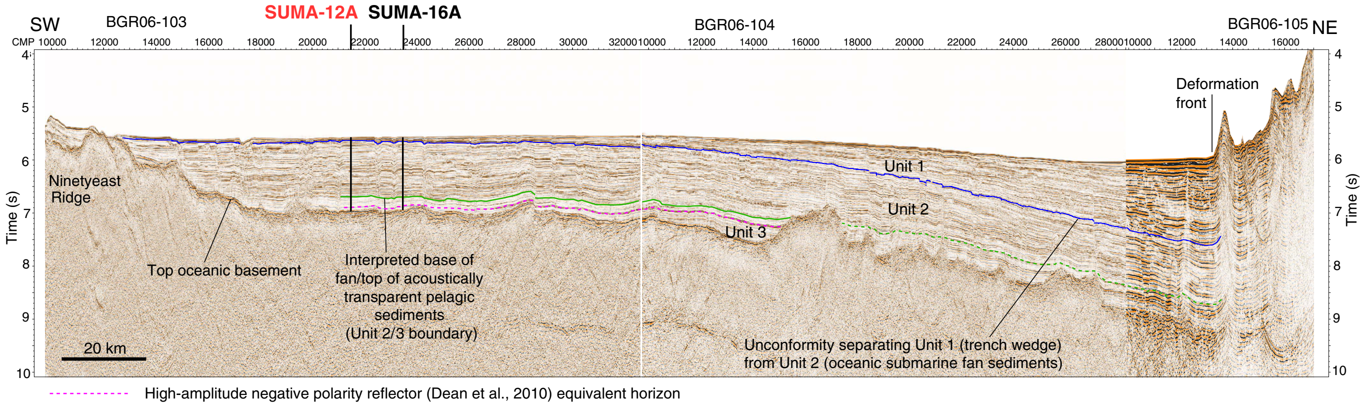


Figure F7. Seismic Profile BGR06-102 showing proposed primary Site SUMA-11C. See Figure **F2** for line location.

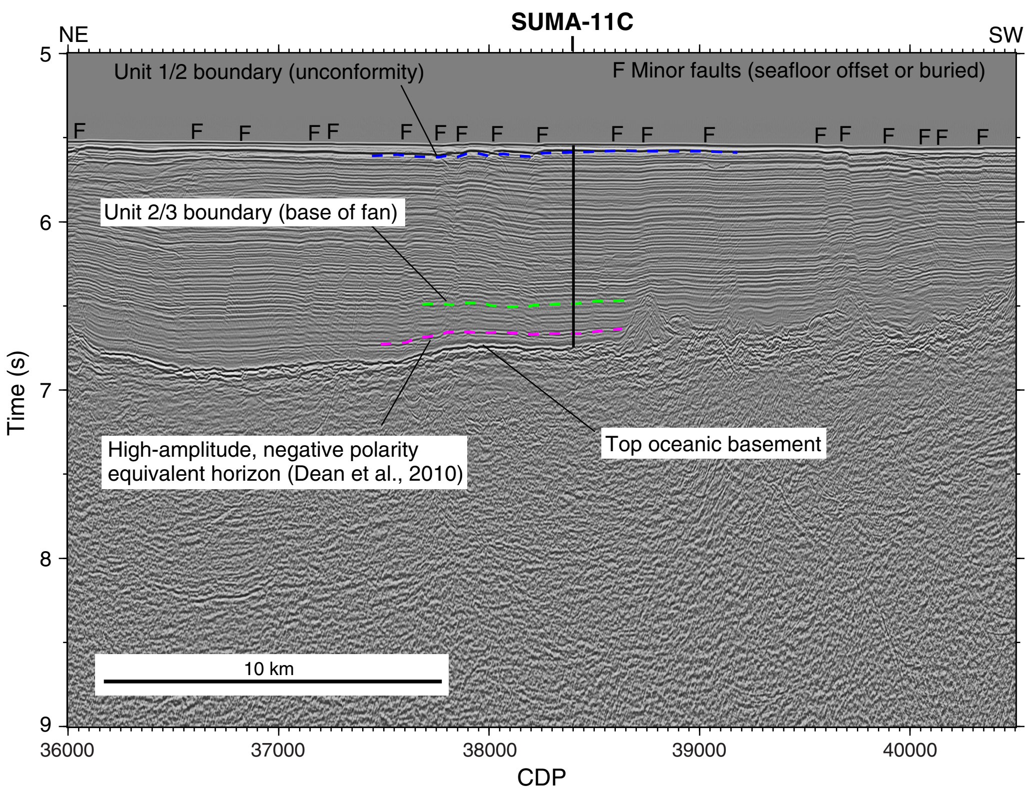
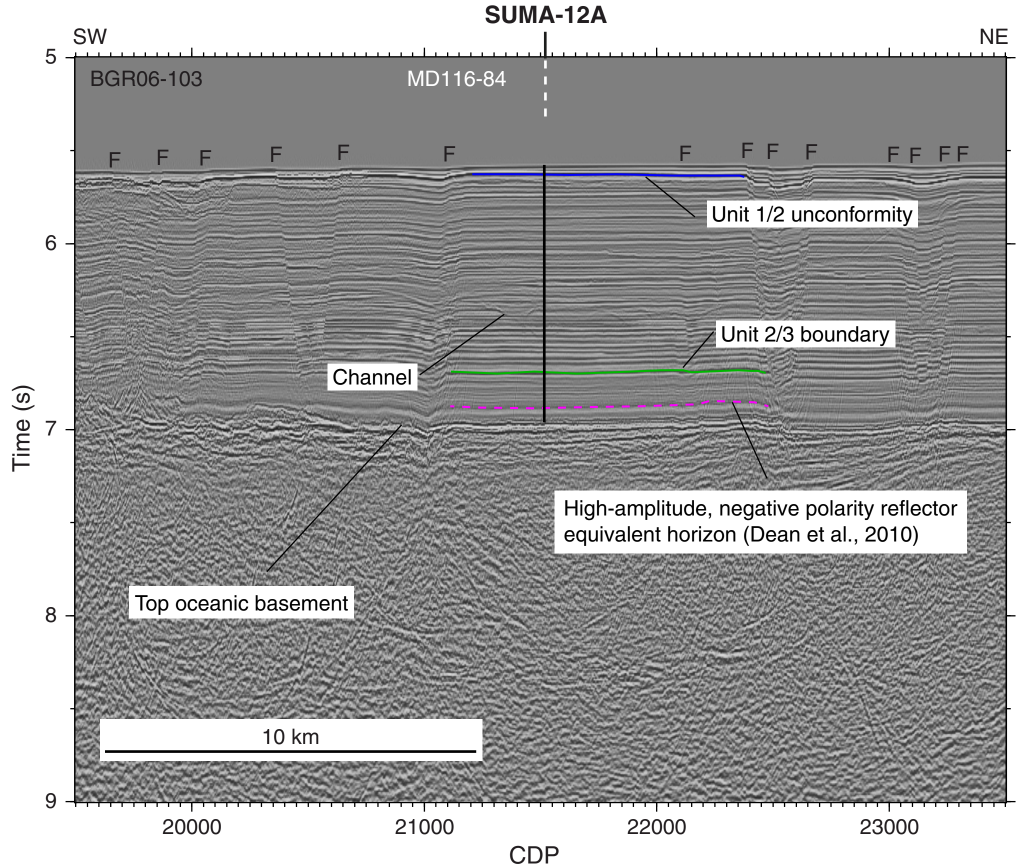


Figure F8. Seismic Profiles BGR06-103 and MD116-84 showing proposed primary Site SUMA-12A. See Figure **F2** for line location. F = minor faults (seafloor offset or buried). Predominantly normal offset with possible strike-slip component.



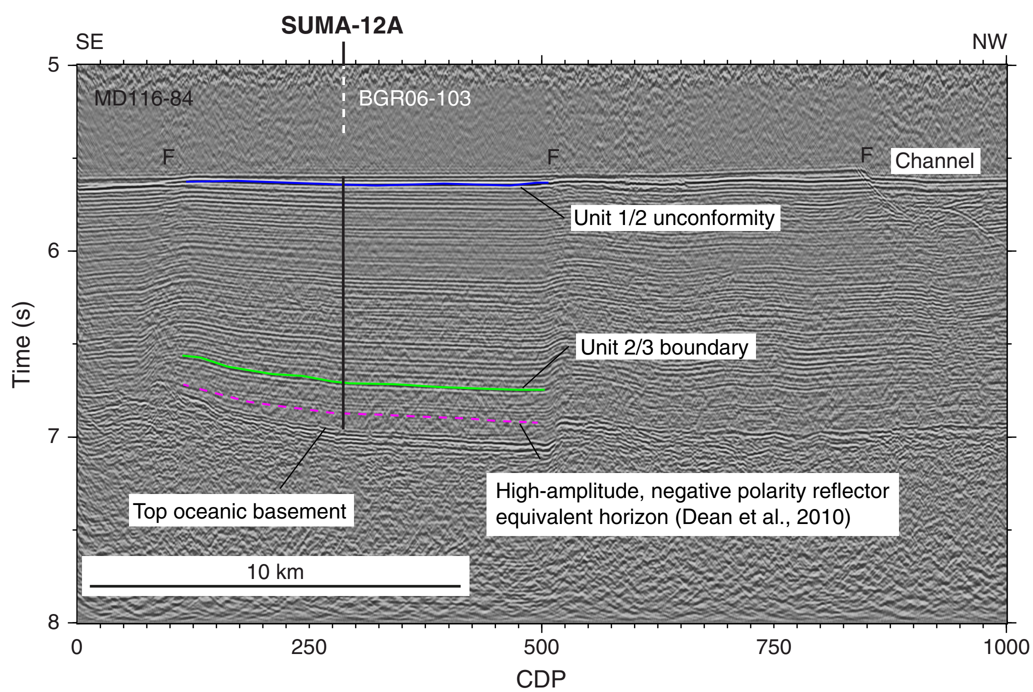
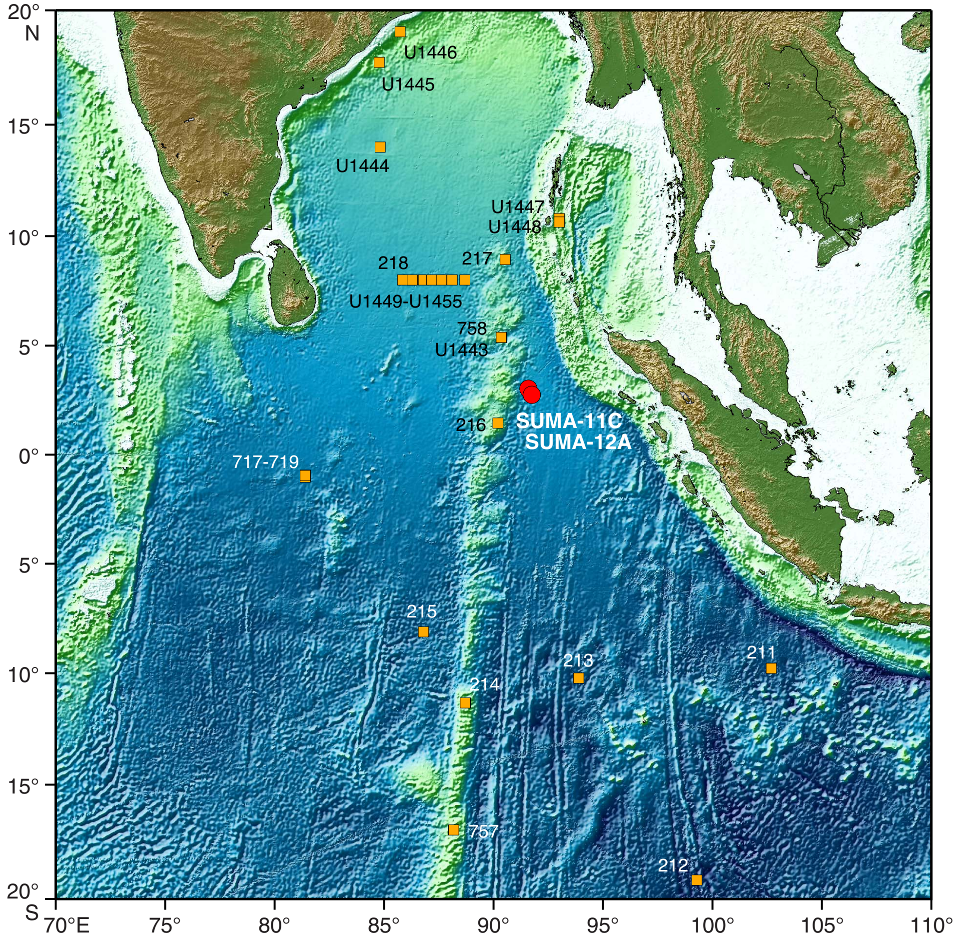


Figure F9. Regional physiography of the eastern Indian Ocean with existing (squares) and proposed (circles) Expedition 362 drill sites. The Nicobar Fan is located between the Ninetyeast Ridge and the Sunda subduction zone.



Site summaries

Site SUMA-11C

Priority:	Primary
Position:	3°2.0448′N, 91°36.3483′E
Water depth (m):	4169
Target drilling depth (mbsf):	1460
Approved maximum penetration (mbsf):	1460 (to basement + 10 m)
Survey coverage:	MCS Profile BGR06-102, CDP 38400 • Track map (Figure **F2B**) • Seismic profile (Figures **F5**, **F7**)
Objective(s):	Core and wireline log lower section of the input sediments: • Age, lithology, physical and thermal properties, sedimentation history of lower section input sediments on the Indian oceanic plate (Nicobar Fan) • Postexpedition experimental and numerical analysis of changing sediment material properties and mechanical behavior with increased burial both pre- and postaccretion • State of stress within the oceanic plate
Drilling coring, and downhole measurements program:	• Hole A: APC/XCB to 800 mbsf • Hole B: reentry system with single casing string • Hole B: RCB from 500 to 1460 mbsf • IceField core orientation measurements • Formation temperature and pressure (APCT-3, SET, SETP, T2P) • Wireline logging (triple combo-UBI, FMS-sonic, VSI)
Nature of rock anticipated:	Hemipelagic, pelagic, sediment gravity-flow (including turbidite) muds, thin silts, and sands

Site SUMA-11B

Priority:	Alternate
Position:	3°5.7323′N, 91°40.0758′E
Water depth (m):	4166
Target drilling depth (mbsf):	1610
Approved maximum penetration (mbsf):	1610 (to basement + 10 m)
Survey coverage:	MCS Profile BGR06-102, CDP 36850 • Track map (Figure **F2B**) • Seismic profile (Figure **F6**)
Objective(s):	Core and wireline log lower section of the input sediments: • Age, lithology, physical and thermal properties, sedimentation history of lower section input sediments on the Indian oceanic plate (Nicobar Fan) • Postexpedition experimental and numerical analysis of changing sediment material properties and mechanical behavior with increased burial both pre- and postaccretion • State of stress within the oceanic plate
Drilling coring, and downhole measurements program:	• Hole A: APC/XCB to 800 mbsf • Hole B: reentry system with single casing string • Hole B: RCB from 800 to 1610 mbsf • IceField core orientation measurements • Formation temperature and pressure (APCT-3, SET, SETP, T2P) • Wireline logging (triple combo-UBI, FMS-sonic, VSI)
Nature of rock anticipated:	Hemipelagic, pelagic, sediment gravity-flow (including turbidite) muds, thin silts, and sands

Site SUMA-12A

Priority:	Primary
Position:	2°45.2857′N, 91°45.5771′E
Water depth (m):	4200
Target drilling depth (mbsf):	1610
Approved maximum penetration (mbsf):	1610 (to basement + 10 m)
Survey coverage:	MCS Profiles BGR06-103, CDP 21512, and MD116-84, CDP 286 • Track map (Figure **F2B**) • Seismic profile (Figures **F6**, **F8**)
Objective(s):	Core and wireline log lower section of the input sediments: • Age, lithology, physical and thermal properties, sedimentation history of lower section input sediments on the Indian oceanic plate (Nicobar Fan) • Postexpedition experimental and numerical analysis of changing sediment material properties and mechanical behavior with increased burial both pre- and postaccretion • State of stress within the oceanic plate
Drilling coring, and downhole measurements program:	• Hole A: APC/XCB to 650 mbsf • Hole B: reentry system with single casing string • Hole B: RCB from 640 to 1610 mbsf • IceField core orientation measurements • Formation temperature and pressure (APCT-3, SET, SETP, T2P) • Wireline logging (triple combo-UBI, FMS-sonic, VSI)
Nature of rock anticipated:	Hemipelagic, pelagic, turbiditic muds, silts, and thin silts/sands

Site SUMA-16A

Priority:	Alternate
Position:	2°48.9647′N, 91°51.2938′E
Water depth (m):	4199
Target drilling depth (mbsf):	1620
Approved maximum penetration (mbsf):	1620 (to basement + 10 m)
Survey coverage:	MCS Profile BGR06-103, CDP 23524 • Track map (Figure **F2B**) • Seismic profile (Figure **F6**)
Objective(s):	Core and wireline log lower section of the input sediments: • Age, lithology, physical and thermal properties, sedimentation history of lower section input sediments on the Indian oceanic plate (Nicobar Fan) • Postexpedition experimental and numerical analysis of changing sediment material properties and mechanical behavior with increased burial both pre- and postaccretion • State of stress within the oceanic plate
Drilling coring, and downhole measurements program:	• Hole A: APC/XCB to 800 mbsf • Hole B: reentry system with single casing string • Hole B: RCB from 800 to 1620 mbsf • IceField core orientation measurements • Formation temperature and pressure (APCT-3, SET, SETP, T2P) • Wireline logging (triple combo-UBI, FMS-sonic, VSI)
Nature of rock anticipated:	Hemipelagic, pelagic, sediment gravity-flow (including turbidite) muds, thin silts, and sands