Integrated Ocean Drilling Program Expedition 344 Scientific Prospectus

Costa Rica Seismogenesis Project, Program A Stage 2 (CRISP-A2)

Sampling and quantifying lithologic inputs and fluid inputs and outputs of the seismogenic zone

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Abstract

The Costa Rica Seismogenesis Project (CRISP) is designed to elucidate the processes that control nucleation and seismic rupture of large earthquakes at erosional subduction zones. CRISP is located at the only known seismogenic zone at an erosional margin within reach of scientific drilling. With a low sediment supply, fast convergence rate, abundant seismicity, subduction erosion, and a change in subducting plate relief along strike, CRISP offers excellent opportunities to better understand earthquake nucleation and rupture propagation. This project complements other deep fault drilling (San Andreas Fault Observatory at Depth and Nankai Trough Seismogenic Zone Experiment) and investigates the first-order seismogenic processes common to most faults and those unique to erosional margins. Expedition 344 is based in part on CRISP Program A (Integrated Ocean Drilling Program Proposal 537A-Full5), which is the first step toward deep riser drilling through the seismogenic zone. This expedition will focus on constraining the boundary conditions of lithology, fluid flow, and thermal structure that trigger unstable slip in the seismogenic zone along a drilling transect at two slope sites. These slope sites may also serve as pilot holes for potential future proposed riser drilling to reach the aseismic/seismic plate boundary.

Schedule for Expedition 344

Expedition 344 is based partly on Integrated Ocean Drilling Program (IODP) drilling proposal 537A-Full5 (Costa Rica Seismogenesis Project [CRISP] Program A; available at **iodp.tamu.edu/scienceops/expeditions/costa_rica_seismogenesis.html**) and Expedition 334 (Expedition 334 Scientists, 2011). Following ranking by the IODP Scientific Advisory Structure, Expedition 344 was scheduled for the research vessel R/V *JOIDES Resolution*, operating under contract with the US Implementing Organization (USIO). At the time of publication of this *Scientific Prospectus*, the expedition is scheduled to start in Balboa, Panama, on 23 October 2012 and to end in Puntarenas, Costa Rica, on 11 December 2012. A total of 49 days will be available for the drilling, coring, and downhole measurements described in this report (for the current detailed schedule, see **iodp.tamu.edu/scienceops/**). Further details about the facilities aboard the *JOIDES Resolution* and the USIO can be found at **www.iodp-usio.org/.**

Introduction

The primary objective of CRISP is to better understand the processes that generate earthquakes along the subduction thrust at erosive margins. Drilling and monitoring the plate boundary provides critical data for understanding these systems. Drilling allows sampling of the sedimentary inputs, the framework rock comprising the overriding plate, and the plate boundary and measurements of fluid geochemistry, temperature, and stress. Monitoring studies provide insight as to how these systems change with time.

During the past three decades, tectonically active shallow near-trench areas of convergent margins have been drilled in several areas. These areas include Barbados (Mascle, Moore, et al., 1988; Shipley et al., 1992), the Nankai Trough (Kinoshita, Tobin, Ashi, Kimura, Lallemant, Screaton, Curewitz, Masago, and the Expedition 314/315/316 Scientists, 2009; Taira, Hill, Firth, et al., 1991), and Costa Rica (Kimura, Silver, Blum, et al., 1997; Morris, Villinger, Klaus, et al., 2003). However, to better understand natural hazards such as the generation of earthquakes, tsunamis, and arc volcanism requires drilling to the seismogenic zone. The improved capabilities of IODP allow exploration of the seismogenic zone, a primary scientific objective of the Initial Science Plan for IODP. The Costa Rica margin offshore the Osa Peninsula is a region where the processes that lead to the onset of seismicity can be addressed because of abundant seismicity and because the shallow subduction thrust is within the operational capabilities of the IODP riserless drillship (*JOIDES Resolution*) and the seismogenic zone is reachable with the riser drillship (D/V *Chikyu*).

Expedition 344 is based on IODP Proposal 537A-Full (CRISP Program A) and is the continuation of Expedition 334. Like Expedition 334, this expedition will focus on sampling the lithology, characterizing the fluids, and measuring the temperature and stress indicators that lead to a transition from stable to unstable slip. The goals of CRISP Program B are to reach the plate boundary within the seismogenic zone, observe physical conditions, and sample fault zone behavior updip and downdip of large earthquake generation.

Background

The Cocos Ridge and subducting plate

Offshore the western margin of Costa Rica, the oceanic Cocos plate subducts under the Caribbean plate, forming the southern end of the Middle America Trench (Fig. **F1**). A prominent feature of the Costa Rican segment of the Middle America Trench is its along-strike variability. Subduction parameters including the age, convergence rate, azimuth, obliquity, morphology, and slab dip all vary along strike. The age of the Cocos plate at the Middle America Trench decreases from 24 Ma offshore the Nicoya Peninsula to 15 Ma offshore the Osa Peninsula (Barckhausen et al., 2001). Subduction rates vary from 70 mm/y offshore Guatemala to 90 mm/y offshore southern Costa Rica (DeMets, 2001). Convergence obliquity across the trench varies from offshore Nicaragua, where it is as much as 25° oblique, to nearly orthogonal southeast of the Nicoya Peninsula (DeMets, 2001; Turner et al., 2007). This obliquity has implications for slip partitioning as indicated by focal mechanisms and GPS displacement data (Lundgren et al., 1999; McCaffrey, 2002; Norabuena et al., 2004; Turner et al., 2007; LaFemina et al., 2009).

The bathymetry and morphology of the incoming Cocos plate are largely a function of its origin and subsequent history. The Cocos plate was formed at two ridges, the fast-spreading East Pacific Rise (EPR) and the slow-spreading Cocos Nazca spreading center (CNS). The boundary separating EPR from CNS crust is a combination of a triple junction trace and a fracture zone, collectively comprising a "plate suture" (Fig. **F1**). EPR-generated crust has a generally smoother morphology than CNS-generated crust. Subsequent to the plate's formation it was intruded by Galapagos hotspot volcanism. Passage of the Cocos plate over the Galapagos hotspot created the aseismic Cocos Ridge, an overthickened welt of oceanic crust. This ridge is ~25 km thick, greater than three times normal oceanic crustal thickness. The ridge stands 2.5 km high and is characterized by a distinctive Galapagos-type geochemistry. The area just northwest of the EPR/CNS plate suture (Barckhausen et al., 2001) was drilled during Deep Sea Drilling Project (DSDP) Leg 84 and Ocean Drilling Program (ODP) Legs 170 and 205 (Kimura, Silver, Blum, et al., 1997; Shipboard Scientific Party, 1985, 2003). Sills with a Galapagos-type geochemistry were cored at ODP Sites 1039 and 1253, indicating the great lateral extent of hotspot magma intrusion. Northwest of the Cocos Ridge, ~40% of CNS oceanic crust is covered by seamounts that also have a Galapagos-type geochemistry. These seamounts increase the roughness of the seafloor generated by slow spreading and have likely caused substantial subduction erosion of the outer forearc (Ranero and von Huene, 2000) and uplift of the Osa and Nicoya Peninsulas and the Quepos region (Gardner et al., 1992, 2001; Fisher et al., 1998; Sak et al., 2004).

Historical large magnitude plate interface earthquakes (Mw > 7) may correlate with the locations of subducted seamounts or bathymetric relief. Possible examples include the 1992 Nicaragua (McIntosh et al., 2007), 1950 and 1990 Nicoya (Husen et al., 2002), 1983 Osa (Adamek et al., 1987), and 1999 Quepos (Bilek et al., 2003) earthquakes.

The dip and depth of the Wadati-Benioff Zone decreases from Nicaragua to southern Costa Rica. At the Osa Peninsula, the overthickened Cocos Ridge is more buoyant than normal oceanic crust and causes a shallowing of the Wadati-Benioff Zone. The seismically active slab dips ~65° near the Nicaraguan border and shallows a few degrees inboard of the Cocos Ridge. At depths greater than 60 km there is no seismically defined slab landward of the Cocos Ridge (Vergara Muñoz, 1988; Protti et al., 1994).

An outstanding issue for the tectonics of the region is the timing of the Cocos Ridge impinging on the Middle America Trench. Estimates range from ~1 Ma (Hey, 1977; Lonsdale and Klitgord, 1978) to ~5 Ma (Sutter, 1985) to ~20–22 Ma (Lonsdale and Klitgord, 1978; van Andel et al., 1971). The 5 Ma age is based on the emplacement of adakitic arc rocks between 5.8 and 2.0 Ma (Abratis and Wörner, 2001) and thermochronological information on the uplift of the Talamanca Cordillera (Gräfe et al., 2002). However, marine deposition and volcanic flows in the Pliocene Terrabe forearc basin directly inboard of the Cocos Ridge (Kolarsky et al., 1995) raise concerns about this model.

The CRISP drilling area is located in a region where the incoming plate has relatively thin sediment cover, large variations in along-strike bathymetry, and a fast convergence rate. The plate interface is characterized by abundant seismicity.

Upper plate and onland geology

Seismic data along the margin and drilling offshore the Nicoya (Legs 170 and 205) and Osa (Expedition 334) Peninsulas show that the margin is composed of a thick slope sediment apron, a few hundred meters to ~2 km thick, unconformably overlying upper plate basement (von Huene et al., 2000). In the CRISP drilling area, the upper plate is underthrust by sediments and is buttressed by a small frontal prism (Fig. F2). Offshore the Osa Peninsula the frontal prism is 10–12 km thick but diminishes to 3–5 km offshore the Nicoya Peninsula. The forearc basement was not well sampled during Leg 170.

The basement comprising the margin along the CRISP transect is interpreted to be composed of a mélange of oceanic lithologies accreted to the overriding plate prior to the current phase of subduction erosion (Fig. **F3**). The basement is likely the offshore extension of igneous rocks cropping out onshore that consist of the Caribbean Large Igneous Complex (CLIP) and the Quepos and Osa terranes (Ye et al., 1996; Kimura, Silver, Blum, et al., 1997; Vannucchi et al., 2001). The CLIP is composed of accreted ocean islands and aseismic ridge terranes (Hauff et al., 1997, 2000; Sinton et al., 1997; Hoernle et al., 2002). The Quepos and Osa terranes are interpreted to represent rock accreted from subducted edifices generated by the Galapagos hotspot (Hauff et al., 1997; Vannucchi et al., 2006). On land and close to the CRISP transect, the seaward-most unit is the Osa Mélange, which is dominated by basalt, radiolarite, and limestone (Vannucchi et al., 2006). Short-wavelength magnetic anomalies observed on the Osa margin that are interpreted to be localized bodies of igneous rock mixed with sedimentary rocks lend additional support to this interpretation (U. Barckhausen, unpubl. data). The nature and significance of the Osa Mélange has been controversial. One interpretation is that it represents debris flows that were subsequently accreted to the margin (P.O. Baumgartner, pers. comm., 2002). Other interpretations are that the Osa terrane represents a tectonic mélange produced by subduction erosion (Meschede et al., 1999) or an old tectonic mélange developed within material that was accreted prior to the arrival of the Cocos Ridge (Vannucchi et al., 2006). There is no suggestion that the Osa Mélange reflects accretion from the currently subducting plate, and the evidence for active recent tectonic erosion of the forearc is compelling. The Osa Mélange is, to our best knowledge, the unit that forms the forearc basement and which we expect to drill as upper plate basement during CRISP.

A 45 m.y. gap exists in the rock record between the emplacement of the CLIP (74–94 Ma; Sinton et al., 1998), the Quepos and Osa terranes (60–65 Ma), and the dredged rock samples from the Cocos Ridge and related seamounts near the trench (13.0–14.5 Ma; Werner et al., 1999). Accretion during this period may be partially recorded beneath the Osa continental slope-forearc (Hoernle et al., 2002).

Within the margin, a major unknown is the nature of the high-amplitude landward-dipping reflectors cutting through the forearc basement (Fig. **F2**). They branch upward from the plate interface similarly to splay faults (Park et al., 2002). These surfaces may represent old faults, related to a middle Eocene–middle Miocene accretionary event, now sealed by the slope apron sediment. A few of these surfaces have offsets at the top of the forearc basement into the slope apron, indicating reactivation as normal faults. Similar reactivated normal faults are observed offshore the Nicoya Peninsula and Quepos terrane (McIntosh et al., 1993; Ranero and von Huene, 2000). The lack of a clear thrust sequence argues against the presence of out-of-sequence thrusts (OOSTs) cutting the forearc. The presence of these discontinuities across the forearc basement can offer preexisting planes of weakness, which can play a role in focusing fluid flow drained from the deeper part of the margin as suggested by the high reflectivity and heat flux. The nature and magnitude of permeability along these discontinuities is unknown. Identifying the nature and age of the landward-dipping reflectors is fundamental to understanding the tectonic history of the margin offshore Osa Peninsula and the process of subduction erosion.

The subduction of the Cocos Ridge is thought to have caused (1) the cessation of the arc volcanism and uplift of the Talamanca Cordillera; (2) the inversion of the middle Eocene–Pliocene forearc basin, now exposed along the Fila Costeña, a fold and thrust belt with peak elevations of 1000–1500 m; and (3) the exhumation of the Late Cretaceous–early Eocene ophiolitic rocks cropping out along the Osa Peninsula gulf and the middle Eocene–middle Miocene Osa Mélange. Directly inboard of the Cocos Ridge, geologic and GPS data reveal maximum uplift and shortening. Quaternary shortening exceeds 15 km (10–40 mm/y) across the Fila Costeña fold and thrust belt (Fisher et al., 2004; Sitchler et al., 2007). The Talamanca Cordillera located between the Fila Costeña fold and thrust belt and the northern Panama deformation belt exposes plutonic rocks as young as 6 Ma (MacMillan et al., 2004), implying rapid uplift.

Volcanic arc

In Costa Rica, $^{40}Ar/^{39}Ar$ dating indicates a maximum age of the volcanic arc of at least 24 Ma (Gans et al., 2002). Plutons intruded the Talamanca Cordillera until the late Miocene, ~7 Ma (Gans et al., 2002; Mora, 1979; Sutter, 1985), after which subduction-related calc-alkaline magmatism diminished. Backarc alkaline magmatism during the following ~6–3 m.y. produced lava flows, dikes, and sills (Abratis and Wörner, 2001). Just south of the central magmatic arc, lavas that erupted from 5.8 to 2.0 Ma have a trace element signature characterizing them as partial melting products of subducted oceanic crust with garnet residue, or adakites, and a plume-related isotope signature (Abratis and Wörner, 2001; Gans et al., 2002).

The Central America volcanic arc was a high-priority study area of the Subduction Factory initiative of the US MARGINS program. Here, variations in subduction dynamics result in sharp differences in the apparent sediment transport to depth, mirroring strong along-strike changes in trace element and isotopic chemistry, such as the ^{10}Be deficit in Costa Rican volcanoes (Morris et al., 2002). The possibility of studying the tephra stratigraphy preserved in the slope apron sediments offshore Osa will help in the along-strike reconstruction of the margin and will open a window in the processes linked to the volcanic arc shutdown when compared to the ash stratigraphy already recovered offshore the Nicoya Peninsula.

Subduction erosion

Drilling and seismic data indicate active and long-lived subduction erosion from Guatemala to Costa Rica (Ranero and von Huene, 2000; Ranero et al., 2000; Vannucchi et al., 2001, 2003, 2004). This interpretation is based on the following:

- Long-term subsidence of the continental slope offshore Nicoya Peninsula. Leg 170 provided direct evidence of shallow-water sedimentary rocks, now located in 3900 m water depth in the forearc. These slope apron–forearc sediments lie unconformably on the basement, demonstrating that the margin offshore Nicoya Peninsula has experienced a net loss of crust since ~16 Ma (Vannucchi et al., 2001). Detailed analysis of the benthic fauna preserved in the slope apron sediment from Legs 84 and 170 indicates that a slow background subsidence of ~20 m/m.y. radically increased to ~600 m/m.y. starting at the Miocene/Pliocene boundary (Vannucchi et al., 2003). This acceleration in subsidence may be linked to the arrival of the Cocos Ridge at the subduction zone (Vannucchi et al., 2003). Faster subduction erosion may be expected to the south where ridge subduction caused severe damage to the margin, as suggested by the disrupted topography (von Huene et al., 2000). The slope offshore Osa has retreated as much as 20 km more than in the Nicoya area, where the subducting plate is smoother and the trench retreat has been estimated at ~50 km since 16 Ma (Vannucchi et al., 2001). Offshore Nicaragua, subsidence driven by tectonic erosion triggered the development of the Sandino forearc basin (Ranero and von Huene, 2000; Ranero et al., 2000).
- The regional extension of the slope apron–forearc unconformity across igneous basement in northern Costa Rica and the middle Eocene–middle Miocene mélange in southern Costa Rica is consistent with subduction erosion.
- Disrupted topography at the base of the slope and in the wake of seamounts. The trench inner slope of Costa Rica is punctuated by subducted seamount tracks

reflecting a net loss of material, and at a larger scale, the whole margin has a broad concavity centered on the Cocos Ridge, testifying to the removal of material through ridge subduction.

Volatiles and fluids

Pathways of fluid flow through the Costa Rica margin include the margin, the décollement, and the underlying oceanic crust (e.g., Silver et al., 2000; Fisher et al., 2003; Hutnak et al., 2007; Sahling et al., 2008; Harris et al., 2010a, 2010b).

Along the entire Costa Rica margin, active fluid venting is indicated by elevated methane concentrations in the bottom water (Kahn et al., 1996; McAdoo et al., 1996; Bohrmann et al., 2002). Chemoautotrophic and methanotrophic communities mark cold vents at numerous localities, but higher concentrations have been found where subducted seamounts have triggered fractures, slides, and slumps that break a low-permeability, shallow sediment carapace, allowing ascending fluids to feed the communities that are particularly concentrated at the headwall scarps (Kahn et al., 1996; Bohrmann et al., 2002; Ranero et al., 2008). Mud volcanoes and mud diapirs have also been found, particularly across the middle slope, and are associated with a high density of chemosynthetic vents. The chemistry of the pore fluids sampled at these mid-slope features is indicative of dehydration reactions at depth, suggesting they are associated with structures that enable effective transport of fluids in the overpressured slope sediments (Shipley et al., 1992; Bohrmann et al., 2002; Grevemeyer et al., 2004; Hensen et al., 2004).

Along the décollement and the upper prism fault zone, Leg 170 coring and sampling revealed freshened pore waters containing elevated Ca, Li, and C3–C6 hydrocarbon concentrations and low K concentrations (Kimura, Silver, Blum, et al., 1997; Silver et al., 2000; Morris, Villinger, Klaus, et al., 2003). These fluids contrast with pore fluids from below the décollement and between the décollement and upper fault zone that have near-seawater chemistry (Kimura, Silver, Blum, et al., 1997; Morris, Villinger, Klaus, et al., 2003). Downhole temperatures measured during Legs 170 and 205 are insufficient to support in situ mineral dehydration and thermogenic methane. Collectively, geochemical data in the décollement offshore Nicoya Peninsula indicate that this flow system is active and a fraction of the fluid is derived from depths within the subduction zone where temperatures are ~80°–150°C (Chan and Kastner, 2000; Silver et al., 2000; Kastner et al., 2006; Solomon et al., 2009). The sharpness of the geochemical anomalies in the décollement and the estimated temperature of the fluid suggest updip flow from a source region ~38–55 km landward of the trench at ~9–14 km depth, near the updip limit of the seismogenic zone (Harris and Wang, 2002; Spinelli and Saffer, 2004; Kastner et al., 2006; Ranero et al., 2008).

The magnitude of the hydrological activity in the subducting oceanic plate is just beginning to be appreciated (Silver et al., 2000; Harris and Wang, 2002; Fisher et al., 2003; Hutnak et al., 2008; Solomon et al., 2009; Harris et al., 2010a, 2010b). Low heat flow values averaging ~30 mW/m^2 exist in the EPR-generated crust offshore the Nicoya Peninsula (Langseth and Silver, 1996; Fisher et al., 2003; Hutnak et al., 2007, 2008). These values reflect <30% of the expected value from conductive lithospheric cooling models for 24 Ma crust (Stein and Stein, 1994), indicating effective hydrothermal cooling of the upper oceanic crust in the study area with recharge and discharge occurring at distant igneous outcrops and seamounts (Fisher et al., 2003). This inference is corroborated by pore fluid chemical and isotopic profiles in basal sediments that show a return to approximate seawater values near the upper part of the igneous basement (Chan and Kastner, 2000; Silver et al., 2000; Morris, Villinger, Klaus, et al., 2003). In addition to the cooling effect, the vigorous lateral flow of seawater must also alter and hydrate the igneous crust, affecting chemical and isotopic mass balances as well as the transfer of volatiles through the subducting slab down to the depth of magma genesis.

Offshore the Nicoya Peninsula, two sealed borehole hydrologic observatories (CORKs) were installed to investigate the relationship between tectonics, fluid flow, and fluid composition (Jannasch et al., 2003; Morris, Villinger, Klaus, et al., 2003; Solomon et al., 2009). One of these CORKs was deployed at ODP Site 1255 with downhole instrumentation designed to monitor formation fluid flow rates, composition, pressure, and temperature in a screened interval in the décollement. The other CORK was deployed at ODP Site 1253 with downhole instrumentation to measure fluid pressure, temperature, and chemistry in the subducting igneous basement. The initial 2 y record was recovered in September 2004, and a second record was recovered in February 2009. The long-term pore fluid pressure record at Site 1255 showed a near-steady-state pressure that was only moderately superhydrostatic with a pore pressure ratio (λ^*) of ~0.2 (Davis and Villinger, 2006), and flow rates averaged ~1.0 cm/y during the 2002–2004 deployment period (Solomon et al., 2009). Two positive transients in fluid pressure, flow rates, and composition were observed along the décollement between 2002 and 2004 (Davis and Villinger, 2006; Solomon et al., 2009). Both transients coincided with onshore deformational events recorded at continuously monitored GPS stations on the Nicoya Peninsula ~2 weeks prior to being recorded near the trench at the CORK (Protti et al., 2004). These two transients have been interpreted as the result of aseismic slip dislocations that propagated updip over the course of ~2 weeks, terminating before reaching Site 1255 and the trench (Solomon et al., 2009), and indicate that slow slip events propagate through the seismogenic zone to the trench at the Costa Rica subduction zone.

The continuous fluid pressure, temperature, and chemistry record obtained from the CORK at Site 1253 shows that the pressure in uppermost igneous basement is ~6 kPa subhydrostatic (Davis and Villinger, 2006), indicating the upper basement is highly permeable. The average fluid flow rate measured at the Site 1253 CORK is 0.3 m/y, and the fluid chemistry in the basement indicates that the basement fluid is actually a mixture between seawater (~50%) from the regional fluid flow system and a subduction zone fluid originating within the forearc (~50%) (Solomon et al., 2009). These results suggest that the uppermost basement offshore Nicoya Peninsula serves as an efficient pathway for fluid expelled from the forearc.

Offshore Osa Peninsula, heat flow values are much higher than at Nicoya Peninsula (averaging ~130 mW/m^2) (von Herzen and Uyeda, 1963; Vacquier et al., 1967). The Cocos Ridge upper crust is well layered and probably very permeable (C.R. Ranero, pers. comm., 2003). The contribution from the lower plate to the fluid circulation could also be significant in the CRISP drilling area. Results from Expedition 334 and Expedition 344 drilling and sampling will help clarify fluid sources and pathways in this segment of the Costa Rica margin.

Seismogenic zone and earthquakes

CRISP Program A is preparatory to the seismogenic zone experiment and will define the tectonic reference for deeper drilling. The most recent seismic sequence along the Costa Rican seismogenic zone occurred offshore the Osa Peninsula in 2002 (Fig. **F4**). This sequence nucleated in the southeastern region of the forearc where a seamount has been thrust under the margin. A Mw = 6.9 earthquake sequence occurred in 1999 and collocated with a subducted ridge and associated seamounts. The 2002 Osa mainshock and first few hours of aftershocks began in the CRISP drilling area ~30 km of the 1999 sequence. In the 2 weeks following the mainshock, aftershocks migrated both into the 1999 aftershock area and updip of the mainshock (Arroyo et al., 2011).

GPS measurements on land indicate that over the subducted Cocos Ridge most of the plate interface in the seismogenic region is essentially fully locked (Dixon, 2003;

LaFemina et al., 2009). In contrast, seismic profiles indicate fault geometries (i.e., angles between forethrusts, backthrusts, and the décollement) that suggest low values of plate boundary friction (von Huene et al., 2000, 2004; von Huene and Ranero, 2003). These values are comparable to the shear strength of marine sediment and may accommodate seafloor relief at the front of the margin without much deformation. One model has fluids draining from the subducting lower plate sufficient to hydrofracture and to mobilize about a 1–2 km thick and 20 km long section of the upper plate material every 1 m.y. in Central America (von Huene et al., 2004).

Site survey data

The supporting site survey data for Expedition 344 are archived at the **IODP Site Survey Data Bank.**

The regional framework of the Central America Trench off Costa Rica is well known from investigations since DSDP drilling in the early 1980s (Aubouin et al., 1982) and later, Legs 170 and 205 (Kimura, Silver, Blum, et al., 1997; Morris, Villinger, Klaus, et al., 2003). Recently, this margin has been the focus of two major scientific projects: the German Collaborative Research Center (SFB) 574 "Volatiles and fluids in subduction zones" (**sfb574.ifm-geomar.de/home/**) and the US MARGINS National Science Foundation program (**www.nsf-margins.org/SEIZE/CR-N/CostaRica.html**).

More than 10,000 km of bathymetric imaging has been acquired (swath bathymetry; Weinrebe and Ranero, in GeoMapApp and MARGINS Data Portal; **www.geomapapp.org/**) (Fig. **F5**). The extensive multibeam bathymetric mapping shows variable seafloor morphology between the Nicoya and Osa Peninsulas (von Huene et al., 1995). The multibeam bathymetry is complemented by several deep-towed instrument traverses. The towed ocean bottom instrument (TOBI) sidescan sonar system of the Southampton Oceanography Centre was used during SO-163 in the spring of 2002 to detect active fluid flow at seafloor mounds and mass wasting offshore Costa Rica (Weinrebe and Ranero, 2003). Together with the results of the TOBI survey during the SO-144 cruise in 1999, much of the continental margin from Costa Rica to southeast Nicaragua was imaged with a resolution on the order of 10 m. Parts of that surveyed area were imaged with greater resolution using the GEO-MAR DTS-1 deep-towed sidescan sonar system to map key areas with a resolution of better than 1 m (Klaucke et al., 2008; Petersen et al., 2009). Observations of the seafloor with a TV sled, gravity coring, and a TV-guided grab (Flüh et al., 2004) pinpointed areas of interest. Widespread mounds, some tens of meters high and a few hundred meters wide, have been monitored with current meters and hydrographic stations (Flüh et al., 2004). Outcropping carbonates on top and at the flanks indicate that these mounds are formed by chemoherm carbonates with abundant signs of fluid flow (Bohrmann et al., 2002; Hensen et al., 2004).

A local network of stations on land has recorded seismicity in the area for 2 decades (Fig. **F4**). Several marine seismological networks of ocean-bottom seismometers (OBS) and ocean-bottom hydrophones (OBH) have been deployed offshore Costa Rica. The Costa Rica Seismogenic Zone Experiment (CRSEIZE), run by University of California Santa Cruz, University of California San Diego, Observatorio Vulcanologico y Sismologico de Costa Rica, and University of Miami, established two seismic networks off the Osa and Nicoya Peninsulas. The first network was a 3 month (September–November 1999) onshore and offshore deployment between Quepos and the north shore of the Osa Peninsula, recording aftershocks from the 20 August 1999 Mw 6.9 underthrust earthquake. The second network operated onshore and offshore the Nicoya Peninsula from December 1999 to June 2000 (Newman et al., 2002; DeShon et al., 2006). CRSEIZE also included GPS campaigns across Costa Rica (Norabuena et al., 2004). German SFB 574 deployed OBS and land stations for >9 months (i.e., from the beginning of October 2002 [R/V *Meteor* Cruise M54-3B] to August 2003 [R/V *Sonne* Cruise SO173-1]) (Flüh et al., 2004). SO 173-1 also deployed another 2 months of OBS offshore in 2002.

Geophysical data acquisition in the proposed Osa drilling area is extensive. The proposed drilling sites are positioned on an OBS/OBH seismic refraction transect across the entire onshore/offshore of Costa Rica (Ye et al., 1996; Stavenhagen et al., 1998) (Fig. **F3**). These data were acquired in 1995/1996 during the Trans Isthmus Costa Rica Scientific Exploration of a Crustal Transect (TICOSECT) project. The TICOSECT transect is coincident with three multichannel seismic reflection surveys. The first was shot in 1978 (IG2903 vessel *Ida Green*), later reshot by Shell Oil (Kolarsky et al., 1995), and shot again in 1999 (BGR99 vessel *Prof. Polshkov*) with a long streamer and an industry acquisition system (Fig. **F2**). Proposed sites have cross-lines of industry and academic heritage. Transducer and high-resolution sparker coverage are available. Conventional heat probe transects were acquired regionally and along the primary transect, which calibrate bottom-simulating reflector (BSR)-derived heat flow from the seismic records (Ranero et al., 2008; Harris et al., 2010a). Magnetic and gravity data cover the area (Barckhausen et al., 1998, 2001). GPS geodesy has been studied for more than a decade, and results show a locked Osa Peninsula area (LaFemina et al., 2009).

Seismic reflection data

Seismic reflection data across the margin are substantial (Fig. **F5**), mainly coming from Cruises *Sonne* SO-76, SO-81 (Hinz et al., 1996; von Huene et al., 2000; Ranero and von Huene, 2000; Ranero et al., 2007), and BGR99 (Ranero et al., 2008). Seismic Line P1600 is provided by Shell (von Huene et al., 2000). All seismic lines were collected with large tuned air gun arrays and multichannel streamers, as described in the original papers. Seismic data have been processed for signal enhancement, including deconvolution and multiple attenuation, and were poststack time migrated. Selected sections are prestack depth migrated. All lines provide good imaging of the structure of the overriding plate including the sediment cover strata, BSRs, and plate boundary reflections.

Seismic reflection data from SO-81 (Hinz et al., 1996) complement those acquired during Cruise BGR99. Two BGR99 records are processed in depth and the remainder in time domains. The principal site survey line (BGR99-7) is flanked on either side by two lines at 1 km spacing, then by lines at 2 km, 5 km, and 10 km spacing (Fig. **F6**). Although these are the most revealing seismic images, other industry and academic acquired records in the area are numerous. Unfortunately, the resources are not available to process them to their full potential. Seismic reflection images collected between Osa Peninsula and the Cocos Ridge (Fig. **F6**) show more stratified forearc basement and lower velocity material (~1 km/s less) than in equivalent areas along the Nicoya transect.

In April and May of 2011, a three-dimensional (3-D) seismic reflection data volume was acquired offshore Costa Rica, northwest of the Osa Peninsula and northwest of the Expedition 334 transect, together with high-resolution backscatter and multibeam data. The goal of the 3-D seismic survey is to illuminate the crustal structure and deformation history of this erosive margin and to image the plate-boundary fault from the trench into the seismogenic zone. The 3-D survey covered 55 km across the upper shelf and slope and into the trench. The survey extends 11 km along strike for a total survey area of 11 × 55 km^2. These data were acquired with the R/V *Langseth* using a 3300 in^3 source shot every 50 m. Data were recorded on four 6 km long, 468-channel streamers with 150 m separation. At the time of this *Scientific Prospectus,* preliminary results from processing two-dimensional (2-D) seismic lines extracted from the 3-D volume and from initial 3-D volume processing were available (Bangs et al., 2011; Kluesner et al., 2011). Initial processing of the seismic data shows an upper plate structure with numerous faults, many extending down to the plate interface, and intense folding and faulting of the slope cover sequences (Bangs et al., 2011). Multibeam data across the shelf and slope correlate to faulting and folding sequences in the slope cover and deeper upper-plate faulting seen in preliminary 2-D and 3-D seismic reflection images. The arcuate structure of the shelf edge and structural bulge seen in seismic data just landward of the shelf edge are consistent with a site of uplift over a subducting ridge (Kluesner et al., 2011).

Heat flow data

Values of surface heat flow vary greatly offshore Costa Rica and have important implications for the thermal state of the shallow subduction thrust and thermally mediated processes along the subduction thrust (Fig. F7). Regional heat flow measurements on the incoming Cocos plate reveal large along-strike variations in heat flow (von Herzen and Uyeda, 1963; Vacquier et al., 1967). EPR-generated seafloor of the Cocos plate has low heat flow relative to the global mean for crust of the same age. The mean value and standard deviation of regional heat flow data on EPR seafloor are approximately 30 and 15 mW/m^2, respectively. For seafloor of this age, conductive predictions are ~100–130 mW/m^2 (Stein and Stein, 1992). In contrast, heat flow values on CNS-generated seafloor are close to the conductive prediction but above the global mean for crust of this age. These values exhibit large variability indicative of fluid flow with a mean and standard deviation of 110 and 60 mW/m^2 for EPR- and CNS-generated crust, respectively.

In 2000 and 2001, heat flow studies specifically designed to investigate the nature of the thermal transition between the cold EPR and warm CNS crust were undertaken (Fisher et al., 2003; Hutnak et al., 2007, 2008). Closely spaced heat flow values collocated with seismic reflection lines show a sharp transition (<5 km) between warm and cool seafloor seaward of the trench that grossly corresponds to the area of the plate suture (Fig. F7). The sharp transition indicates a shallow source consistent with fluid flow in the upper oceanic crust. The thermal boundary between warm and unusually cool values deviates from the plate suture and appears to be influenced by the proximity of basement highs that penetrate the otherwise ~300–400 m thick sediment cover. This exposed basement on EPR accreted crust focuses discharge and efficiently ventilates the oceanic crust.

Probe measurements and BSR estimates of heat flow on the margin (Fig. F7) are discussed by Harris et al. (2010a, 2010b). These profiles show strong variations along strike consistent with regional heat flow data on the incoming Cocos plate. Along the margin underthrust by EPR crust, heat flow is low (Langseth and Silver, 1996; Fisher et al., 2003; Hutnak et al., 2007), whereas along the margin underthrust by CNS crust, heat flow is generally high. The transition between low and high heat flow correlates with the extension of the plate suture and appears relatively abrupt. High wave number variations in the heat flow data are interpreted as focused fluid flow through the margin near the deformation front (Harris et al., 2010a, 2010b).

Scientific objectives

The CRISP program is designed to help us understand seismogenesis along erosional convergent margins. CRISP Program A is the first step toward deep riser drilling through the seismogenic zone. The program focuses on the characterization of the upper plate, lithology, deformation, and fluid system. An evaluation of the subduction channel thickness, necessary to constrain the structural environment that will be drilled during the deep riser drilling, is also a priority of CRISP Program A.

Expedition 344 is a continuation of Expedition 334; together these expeditions comprise Stages 1 and 2 of CRISP Program A. The principal objective of CRISP Program A is to establish the boundary conditions of the Costa Rica erosive subduction system. Proposed work includes the following primary goals.

1. Estimate the composition, texture, and physical properties of the upper plate material.

The upper plate material constitutes a primary input into the erosive plate boundary. As the plate boundary migrates upward, upper plate material is dragged into the subduction channel, which then becomes the input to the seismogenic zone. The onset of seismogenic behavior along the subduction thrust is influenced by physical properties of the overriding plate material. Geologic characterization of the upper plate basement will provide structural and mechanical constraints on the possible mechanical changes occurring at seismogenic depths. Sampling rocks of the upper plate basement beneath the upper slope is necessary to define drilling conditions for deep holes and better constrain hypotheses for testing during CRISP Program B.

Seismic velocities and structure indicate that upper plate basement could correlate with outcrops of mélange on the Osa Peninsula. Onland exposures of the Osa Mélange indicate the accretion of at least two seamounts occurring as events scattered in time—early Eocene/middle Oligocene and middle Miocene—that supply rather different rocks to the margin. The mélange of a third seamount edifice could characterize the upper plate basement of the drilling area. Furthermore, mélanges carry implicit reference to heterogeneity with implications for permeability and fluid pressure.

2. Assess the subduction channel thickness and the rate of subduction erosion.

The actively slipping plate boundary interface is located within the subduction channel. Estimating the subduction channel thickness is critical for preparatory structural geology work and describing the active slip surface and the damage zone for CRISP Program B. Assessing the subduction channel thickness, the zone of broken upper-plate material currently subducting, will be based on the quantification of mass removal in the CRISP study area. A two-point recovery of fossiliferous sediment across the margin will allow the crustal loss rate to be determined through the evaluation of a subsidence profile. Offshore Nicoya, the estimated volume of eroded upper plate rock carried down the subduction zone is essentially four times the volume of subducted trench sediment. Results from Expedition 334 indicate large rates of subduction erosion and sediment accumulation (Expedition 334 Scientists, 2011).

3. Evaluate fluid/rock interaction, the hydrologic system, and the geochemical processes (indicated by composition and volume of fluids) active within the upper plate.

We expect that the Cocos Ridge subduction caused extended fracturing of the upper plate that modified the hydrological system (e.g., flow paths, velocities, heat flow, and mass transport). Landward-dipping reflectors cutting through the upper plate have been interpreted to connect all the way to the plate boundary. Geochemistry can open a window directly to the seismogenic zone through the analysis of parameters that can be related to chemical reactions or mineral precipitation occurring at the depth of seismogenesis.

Fluids are also a key control factor on seismicity because fluid pressure is a physical variable defining the stress state and it is a parameter of the friction laws. Fluid pressure and temperature control the strength of the rocks. Stress state and deformation processes, in turn, influence porosity and permeability and, consequently, fluid pressure. Hence, measuring the thermal and hydrologic regime is critical. Fluid pressure and temperature may be measured in situ until a depth where the material is semiconsolidated. Laboratory analysis, as consolidation tests, can give indirect, but realistic, values of pore pressure.

4. Measure the stress field across the updip limit of the seismogenic zone.

The stress field may be inferred from borehole breakouts. Both GPS investigations and the pattern of microearthquake epicenters indicate a highly stressed area in the vicinity of the Osa Peninsula, implying that relative plate motion in the seismogenic zone is primarily accommodated by coseismic frictional slip. CRISP Program A drilling will contribute to a better definition of the orientation of the horizontal compressive stress in the area. Downhole in situ heat flow measurements will improve our understanding of the thermal regime, allowing better temperature estimates associated with the onset of seismicity as well as allowing us to develop viscoelastic models of deformation.

CRISP Program A is also considered a standalone project providing data to solve longstanding problems related to tectonics of the region. These primary objectives are as follows.

1. *Cocos Ridge subduction.*

Determining the Cocos Ridge subduction arrival time and its effects on the margin tectonics (e.g., acceleration of tectonic erosion processes).

2. *Evolution of the Central America volcanic arc.*

The most relevant effects would be the timing of the progressive shutoff of the volcanic arc and the uplift of the Talamanca Cordillera.

3. *Death of a volcanic arc.*

Determining its time progression and the identification of potential late products from the death of a volcanic arc. This subject can be explored in detail because we would have at least two sedimentary columns to correlate events and thereby explore the consequences of the time-progressive subduction of the Cocos Ridge.

Preliminary results from Expedition 334 (CRISP-A1)

Because of the abbreviated operation schedule of Expedition 334, the first objective was addressed at only three locations on the incoming plate (Site U1381), the middle slope (Sites U1378 and U1380), and the upper slope (Site U1379). The two primary slope sites (Sites U1378 and U1379) were characterized with logging-while-drilling (LWD) data. Subsequently, fluids, sediment, and the underlying upper plate basement at these sites were sampled. A third slope location (Site 1380) was attempted but abandoned because of poor drilling conditions. Finally, the incoming Cocos plate was drilled at Site U1381.

Mid-slope drilling at Site U1378, above the unlocked portion of the plate interface (LaFemina et al., 2009), penetrated 523.9 m below seafloor (mbsf) of slope sediments before drilling was terminated because of poor hole conditions. As a result of poor drilling conditions, basement was not recovered at this site and the high-amplitude reflector interpreted as a displacement surface was not intersected. Recovering mid-slope sediments and basement remains a high priority for Expedition 344. The recovered sediments have a terrigenous origin and consist of an upper unit of silty clay with a series of fining-upward sequences of lithic sands and tephras (Expedition 334 Scientists, 2011) (Fig. F8). The lower unit consists of massive, well-consolidated terrigenous clayey silt(stone) and silty clay(stone) with minor layers of sand(stone), sandy silty clay, clay, and clayey silt(stone). Throughout this lower unit, fining- and coarsening-upward decimeter-scale sequences of sand are present. In the coarser sand layers, rip-up clasts, rounded clay lenses, and abundant shell fragments are common. Low-angle bedding (<30°) planes are observed, as well as healed and open faults with relatively steep dips. Sediment-filled vein structures are also observed. Physical properties data display patterns consistent with normal compaction patterns, including an increase in wet bulk density values and decreasing porosity. Heat flow is 44 mW/m^2, consistent with a forearc setting. In general, observations are consistent with a terrestrially sourced slope sequence that reflects a downslope environment.

Upper slope drilling at Site U1379, above the locked portion of the plate boundary (LaFemina et al., 2009), penetrated 949 mbsf. Basement penetration was first inferred from LWD measurements that indicated a major change in bulk physical properties (density and resistivity). Somewhat surprising, though, was that the rate of LWD penetration slowed only a little relative to that expected for hard rock. Basement material was drilled at Site U1379 in an effort to characterize the lithological, physical, and frictional properties of upper plate material; however, it remains unclear whether the deepest 70 m of this site represents a transition zone with basement clasts or the basement itself. Presumed basement material consists of breccia with softer matrix (sandstone and siltstone) surrounding blocks of basalt and chert. It is still not known with confidence whether these rocks represent true framework rock or a "transition zone"/ "erosional" layer above framework rock.

Four lithologic units within the sediments are recognized at Site U1379 (Fig. F9). The fifth unit is the breccia. Unit I consists of medium- to coarse-grained sand with abundant shell fragments. Unit II consists of clayey silt(stone) and silty clay(stone) with minor layers of sand(stone), sandy silt(stone) and silty clay(stone), clay, clayey silt(stone), and tephra. Unit III consists of fining- and coarsening-upward sequences of silty sands and sandstone. Unit IV consists of carbonate-cemented medium- to coarse-grained sand with well-rounded, lithic pebble-sized clasts and thick-walled shell shards. Unit V is composed of matrix-supported breccia with clasts of limestone, basalt, and mudstone in a fine sandy matrix intercalated with basalt in the upper part and a sequence of variably sandy and clayey silt in the lower part. Structurally, the upper sediments have gently dipping bedding planes with few faults. These upper sediments overlie a zone of steep bedding dips with greater numbers of faults that overlies the breccia. The lithology and physical properties are consistent with changing depositional conditions in a forearc basin that may range from a near-shore environment to shelf sediments to upper slope sediments (turbidites) interrupted by calcareous mud debris from close fluid venting areas.

Site U1381 on the incoming plate consists of ~99 m of sediments (Fig. **F10**). An additional 72 m of igneous basement was cored. Downhole equilibrium temperatures acquired using the Sediment Temperature Tool (SET) increase linearly with depth and give a least-squares geothermal gradient of 222°C/km. The heat flow calculated using the mean thermal conductivity of 0.8 W/(m·K) is 178 mW/m^2. This value is significantly larger than the half-space prediction for 15 Ma crust (130 mW/m^2) and larger than the observed global average heat flow for crust of this age (77 mW/m^2) (Stein and Stein, 1994). This high heat flow value suggests significant fluid flow within the underlying crust. Geochemical profiles below ~50 mbsf reflect diffusional communication with a fluid with seawater-like chemistry in the igneous basement. These data suggest the lateral flow of modified seawater. A diffusive flux of sulfate from the overlying water column and from the basement aquifer below the sediment section prevents sulfate depletion in this site.

The second objective, to estimate the subduction channel thickness and the rate of subsidence, is being met by analyses of sedimentary phases and benthic foraminiferal fauna. Preliminary biostratigraphic ages obtained from the two slope sites indicate high sediment accumulation rates in the terrestrially sourced slope sequence. Accumulation rates vary between 516 and 236 m/m.y. for the middle slope site (U1378) and between 1035 and 160 m/m.y. at the upper slope site (U1379). These rates are an order of magnitude higher than that of slope sediments offshore Nicoya (38–99 m/m.y.) (Kimura, Silver, Blum, et al., 1997). Detailed research of sedimentary facies and benthic foraminiferal faunal in slope sediments at Sites U1378 and U1379 are keys to estimate the mass removal associated with basal erosion and the thickness of the subduction channel.

The third objective of Expedition 334, to characterize the stress field across the updip limit of the seismogenic zone, is being achieved with the analysis of LWD data. The principal objectives of the LWD program are to document in situ physical properties (natural gamma ray, density, neutron porosity, and resistivity), stratigraphic and structural features, compaction state, and hydrological parameters. Density and radius images were used to determine stress orientations from borehole breakouts. The adnVISION tool collected oriented images of bulk density and borehole radius. Despite its limited azimuthal resolution, the images clearly display vertical bands of large borehole radius in the interval 110–438 mbsf at Hole U1378A and in the interval 292–885 mbsf at Hole U1379A (Expedition 334 Scientists, 2011). These bands are interpreted as borehole breakouts caused by differences in principal horizontal stresses. The average azimuth of the breakouts at Site U1379 is roughly northeast–southwest to east-northeast–west-southwest, indicating that the maximum horizontal stress is oriented northwest–southeast to north-northwest–south-southeast. The average azimuth of the breakouts at Site U1378 is roughly north–south to north-northwest–south-southeast, indicating that the maximum horizontal stress is oriented east–west to east-northeast–west-southwest. These azimuths reveal an in situ stress change from compression within the middle slope to extension at the upper slope, addressing the third objective of the expedition.

The fourth objective involves characterizing the fluid flow system and thermal structure of the erosive margin. These properties affect diagenesis and hydrological parameters (e.g., permeability and pore pressure), which are implicated in regulating the mechanical state of the plate interface at depth. Shipboard geochemical data indicate fluid flow occurring both in slope sediments and on the incoming plate (Expedition 334 Scientists, 2011). In slope sediments, fluid composition indicates transport from deep sources. The flow at each site overprints the general geochemical profiles that are influenced by in situ diagenetic reactions. At Site U1379, a broad brecciated zone cored from ~600 to 800 mbsf contains a fluid with low Cl concentrations and peaks in the concentrations of thermogenic hydrocarbons. At Site U1378, there is a monotonic decrease in Cl, Mg, and K concentrations and an increase in Ca concentrations with depth, suggesting diffusional communication with fluids below the base of the hole. It is likely that this fluid resides in the fault zone imaged in seismic reflection profiles at this site. The geothermal gradient at these two sites is too low to support the in situ production of thermogenic hydrocarbons or extensive clay dehydration, suggesting a deeper source for the fluid and hence its migration from greater depths. On the incoming plate at Site U1381, lateral flow of modified seawater through the upper oceanic crust was identified. Here the geochemical profiles below ~50 mbsf reflect diffusional communication with a fluid with seawater-like chemistry in the igneous basement. A diffusive flux of sulfate from the overlying water column and from the basement aquifer below the sediment section prevents sulfate depletion in this site.

Drilling and coring strategy

Drilling strategy

The overall operations plan and time estimates for Expedition 344 are summarized in Table **T1.** Alternate sites have been selected and are presented in Table **T2.** Time estimates are based on formation lithologies and depths inferred from seismic and regional geological interpretations, including prior drilling in this area (Legs 84, 170, and 205 and Expedition 334). After departing from Balboa, Panama, we will transit for ~1.6 days to the Costa Rica sites and prepare for drilling operations.

On 19 January 2012, the Co-Chief Scientists, seismic experts, and IODP representatives met in College Station, Texas, to discuss moving primary sites from the Expedition 334 transect into the 3-D seismic data volume. At the time of the meeting only preliminary seismic analysis was available. However, seismic data showed that sediments within the 3-D seismic volume northwest of the Expedition 334 transect are significantly thicker. The thickness of sediments substantially increases drilling times and precludes meeting many of the CRISP Program A primary science objectives. Therefore it was decided to retain the sites along the Expedition 334 transect as primary drilling sites, with the exception of Site U1379. At Site U1379 primary science objectives were met during Expedition 334. However, this site was also intended to be the pilot hole for riser drilling that intersects the seismogenic zone. The water depth at this site is too shallow for riser drilling, and as discussed later, this site has been moved into the 3-D seismic volume.

The proposed drilling strategy is to begin by drilling at reference Site U1381 on the incoming Cocos plate (Table **T1;** alternate Site CRIS-19A, Table **T2**). This site has primary objectives of characterizing the incoming sediment section and oceanic crust and understanding the nature of the hydrologic system within the upper oceanic crust. During Expedition 334, two holes were drilled at this site, Holes U1381A and U1381B. Hole U1381A was drilled with the rotary core barrel (RCB) coring system to recover as much sediment and basement as possible within the specified time window. Hole U1381B was RCB drilled to retrieve the uppermost 30 m of sediment for detailed geochemical sampling. During Expedition 344, we will use the advanced piston corer (APC) to basement to collect a high-quality sediment core to supplement the RCB sediment core collected during Expedition 334.

Following drilling at Site U1381 we will move to mid-slope Site U1380 (Table T1; alternate Site U1378 and proposed Site CRIS-12B, Table T2). During Expedition 334, Sites U1378 and U1380 were drilled into the middle slope of the Costa Rica margin but the primary objective of penetrating basement was not achieved because of poor hole conditions. Extra time has been planned for installing casing and cementing through the problematic depth interval.

After the mid-slope site we will drill proposed toe Site CRIS-9A (Table T1). This site is located at the frontal sedimentary prism and represents the base of the slope. This site provides sampling of the plate boundary at shallow depth through the sedimentary frontal prism to define the fault state, composition, and fluid system. Proposed Site CRIS-9A will be drilled through 780 m thick sediments and continue for 200 m into the oceanic basement. Drilling at proposed Site CRIS-9A will allow us to constrain the décollement geometry and deformation at a shallow depth, define fluid pathways, and link these to the seismic cycle.

Finally, we will drill proposed upper slope Site CRIS-13B (Table T1; alternate Sites U1379, CRIS-14A, and CRIS-15B, Table T2). Site CRIS-13B is located above the locked portion of the plate boundary. Drilling here will allow us to characterize fluid flow and the basement beneath the upper slope, which is necessary for understanding the drilling conditions for deep holes. Proposed Site CRIS-13B will be drilled through 1330 m thick sediments and continue for 100 m into basement.

Coring strategy

The first hole at proposed Sites CRIS-9A and CRIS-13B will be cored with the APC/ extended core barrel (XCB) to refusal depth (estimated to be ~500 mbsf). A deeper hole at those sites and at Site U1380 will be drilled without coring by installing a center bit to a depth slightly above the refusal depth of Hole A (e.g., ~490 mbsf), and RCB coring will extend from this depth to the target depth. See the "Site summaries" for exact depths. APC cores will be taken with nonmagnetic core barrels until overpull limits are exceeded.

After completing coring at each site, the holes will be conditioned, displaced with logging mud, and logged as per the logging plan (see **"Downhole measurements strategy"**). As per policy, all holes in continental margins into consolidated sediments will be plugged and abandoned with cement plugs.

Downhole measurements strategy

Wireline logging

Downhole logs will be acquired at the Expedition 344 sites to measure in situ physical properties, estimate compaction, and evaluate permeable horizons. Electrical resistivity and ultrasound images referred to magnetic north will be useful to determine fracture orientations and stress directions and to orient core samples. Downhole logging will also provide key data to correlate depth in the hole with traveltime in seismic sections. These logging measurements include check shot data and formation density and velocity measurements that allow for constructing synthetic seismograms.

Three wireline tool strings are planned for the Expedition 344 sites (Fig. **F11**). The first tool string to be deployed in each hole is the triple combination (triple combo)-Ultrasonic Borehole Imager (UBI), which measures hole diameter, natural gamma ray, bulk density, electrical resistivity, and ultrasonic images of the borehole. The images will be acquired by the UBI, a tool that measures a detailed borehole radius and reflection coefficient image with a rotating ultrasonic beam. We added the UBI to the standard triple combo tool string to attempt measuring borehole breakouts, which indicate the orientation of the in situ principal horizontal stresses. Success in imaging breakouts will depend on favorable conditions (borehole diameter ~12 inches or less; well-preserved breakouts after coring), and even covering a partial depth interval will provide valuable scientific information.

The second Formation MicroScanner (FMS)-sonic tool string will consist of a FMS resistivity imaging tool, a Dipole Sonic Imager (DSI) that measures *P*- and *S*-wave velocities, and a natural gamma ray sensor. The third tool string will be deployed in a check shot experiment where a Versatile Seismic Imager (VSI) records the arrival of acoustic pulses generated by air guns fired from the *JOIDES Resolution*. The FMS-sonic and VSI tool strings will be run depending on ship heave and borehole conditions. Detailed descriptions of wireline tools and operational constraints are at **iodp.ldeo.columbia.edu/TOOLS_LABS/index.html.**

Wireline logging is expected to be challenging at the Expedition 344 sites because deep holes in a convergent margin environment are likely to be unstable after coring. To maximize the chances of obtaining useful logging data, the operations plan (Table **T1**) calls for two stages in logging at two sites. Sites CRIS-9A and CRIS-13B will be cored in two holes: Hole A to ~500 mbsf (cored by APC/XCB) and Hole B to total depth (cored by RCB). The triple combo-UBI and FMS-sonic tool strings will be deployed first to log Hole A and then the deeper interval in Hole B. It will be important to set the drill pipe in Hole B as deep as possible during logging, ideally just above the depth of the shallower Hole A. The drill pipe allows the logging strings to pass through borehole obstructions that may make it impossible to reach the deep interval to be logged. The final drill pipe depth will be determined based on hole conditions and after consultation between the IODP Operations Superintendent, the drilling subcontractor, and the Logging Staff Scientist. The operations plan also includes a check shot survey with the VSI tool string in the deepest holes drilled at Sites CRIS-9A, U1380, and CRIS-13B.

Temperature and core orientation measurements

The scientific objective of the temperature measurement plan is to provide data to reconstruct the thermal gradient at each site. This information will be a key input to estimate heat flow, infer fluid flow, model pore water geochemistry, and constrain the sediment diagenesis history. We plan on deploying the advanced piston coring temperature tool (APCT-3) in the interval where cores will be taken by APC and the SET or sediment temperature pressure (SET-P) tool further downhole where sediments are more consolidated. Temperature measurements will be carried out every 40–50 m down to the maximum depth where the SET tool can penetrate sediment. This maximum depth depends on the formation, and we estimate it to be ~500 mbsf. We also plan to deploy the SET-P tool to measure in situ formation pressure. Taking these measurements will require a stable hole, because the probe needs to be seated in the formation for ~10 min (45 min for pressure) with no drill string rotation and no drilling fluid circulation. APC cores will be oriented with the FlexIt tool for paleomagnetic studies.

Risks and contingency

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

Hole conditions

Poor hole conditions (e.g., encountering thick intervals of loose sediment that can collapse into the hole) will be dealt with by using frequent high-viscosity mud sweeps and/or heavy mud to condition the holes. In addition, the plan at the mid-slope site is to case off the upper section of the hole, which requires the installation of a reentry cone, and to cement selected intervals to stabilize the hole.

Weather conditions

Drilling in shallow water is more challenging than drilling in deep water. In part, this is because the ship must maintain position to within a maximum 8% of water depth. Drilling in shallow water also involves restrictions on the amount of heave that can be tolerated by the heave compensator. The amount of allowable heave increases with water depth within three depth ranges: 76–300 m, 301–650 m, and >651 m. For example, coring will stop if heave exceeds 1 m in water <301 m. Therefore, we must be prepared to modify the drilling strategy in response to changing weather conditions.

Marine mammals

The check shot experiment with the VSI tool can only be performed during daylight hours and with the absence of any marine mammals. If marine mammals are sighted during the experiment, then operations will be suspended as required by IODP guidelines.

Alternate sites

A series of alternate sites are available for contingency operations (Table **T2**). In addition, Site CRIS-20A has been proposed as a contingency site to further characterize the sediments and correlate them with the 3-D seismic survey in case time allows. Seismic profiles of all proposed alternate sites are included in the **"Site summaries."**

Sampling and data sharing strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations policy posted on the Web at **www.iodp.org/program-policies/.** 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.

Shipboard scientists are expected to submit data and sample requests (at **smcs.iodp.org/**) 3 months before the beginning of the expedition. Based on the requests (shore based and shipboard) 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. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. Modification of the strategy during the expedition must be approved by the Co-Chief Scientists, Staff Scientist, and curatorial representative on board ship.

The minimum 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 other requests, and the expedition objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

We anticipate whole-round sampling to document pore fluid chemistry profiles, sediment strength, stress, consolidation, and permeability. We expect the upper plate basement to be formed by a mélange similar to the onland Osa Mélange with gabbro, basalt, radiolarite, carbonate, and sandstone blocks in a clay-rich matrix.

We anticipate developing a coordinated sampling strategy, possibly including the creation of large composite samples, to ensure that multiple analyses can be performed on splits of the same sample. If 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.

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Table T1. Expedition 344 operations plan, primary sites.

Site No.	Location (Latitude, Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling/ Coring (days)	Logging (days)
Balboa, Panama			Begin Expedition 2.0 port call days			
			Transit ~416 nmi to U1381 @ 10.5 knots	1.6		
U1381	8° 25.71' N	2080	Hole C - APC to basement ~100 mbsf;		1.2	
EPSP	84° 9.47' W		APCT-3 temperature measurements, orientation of cores, and non-magnetic core barrels.			
to 350 mbsf						
			Subtotal Days On-Site: 1.2			
			Transit ~11 nmi to U1380 @ 6.0 knots	0.1		
U1380	8° 36.00' N	515	Hole U1380B - Jet-In test		0.7	
EPSP	84° 4.40' W		Hole U1380C - Re-entry system (20" and 16" casing to 260 mbsf)		4.4	
to 800 mbsf			Hole U1380C - Drill to 300 mbsf, RCB to 800 mbsf, cement at intervals to stabilize hole; Log with triple combo, FMS-sonic and VSI		9.2	1.7
			Subtotal Days On-Site: 16.0			
			Transit ~7 nmi to CRIS-9A @ 6.0 knots	0.1		
CRIS-9A	8° 29.33' N	2011	Hole A - APC/XCB to ~500 mbsf; Log with triple combo and FMS-sonic; APCT-3/SET measurements, orientation of cores, and non-magnetic core barrels.		3.2	1.0
EPSP	84° 7.69' W		Hole B - Drill to ~490 mbsf, RCB to 980 mbsf; Log with triple combo, FMS-sonic and VSI		8.3	1.6
to 980 mbsf						
			Subtotal Days On-Site: 14.1			
			Transit ~15 nmi to CRIS-13A @ 6.0 knots	0.1		
CRIS-13B	8° 44.46' N	554	Hole A - APC/XCB to ~600 mbsf; Log with triple combo and FMS-sonic; APCT-3/SET measurements, orientation of cores, and non-magnetic core barrels.		3.1	1.0
EPSP	84° 6.81' W		Hole B - Drill to 590 mbsf, RCB to 1430 mbsf; Log with triple combo, FMS-sonic and VSI		7.1	2.3
to 1430 mbsf						
			Subtotal Days On-Site: 13.5			
			Transit ~85 nmi to Puntarenas @ 10.5 knots	0.3		
Puntarenas, Costa Rica			End Expedition	2.2	37.2	7.6

Port Call:	2.0	Total Operating Days:	47.0
Sub-Total On-Site:	44.8	Total Expedition:	49.0

EPSP = Environmental Protection and Safety Panel, APC = advanced piston corer, APCT-3 = advanced piston coring temperature tool, SET = sediment temperature tool, RCB = rotary core barrel, FMS-sonic = Formation MicroScanner sonic tool string, VSI = Versatile Seismic Imager.

Table T2. Expedition 344 operations plan, alternate sites.

Site No.	Location (Latitude, Longitude)	Seafloor Depth (mbrf)	Operations Description	Drilling/ Coring (days)	Logging (days)
			The following site is an alternate to U1381		
CRIS-19A	8° 30.23' N	2468	Hole A - APC to basement ~400 mbsf; Log with triple combo and FMS-sonic	3.1	0.9
EPSP	84° 13.53' W				
to 500 mbsf					
			Subtotal Days On-Site: 4.0		
			The following sites are alternates to U1380		
U1378	8° 35.54' N	533	Hole U1378C - Jet-In test	0.7	
EPSP	84° 4.63' W		Hole U1378D - Re-entry system (20" and 16" casing to 260 mbsf)	4.5	
to 1000 mbsf			Hole U1378D - Drill to 450 mbsf, RCB to 1000 mbsf, cement at intervals to stabilize hole;	13.7	1.9
			Log with triple combo, FMS-sonic and VSI		
			Subtotal Days On-Site: 20.8		
CRIS-12B	8° 36.45' N	441	Hole A - APC/XCB to ~550 mbsf; Log with triple combo and FMS-sonic	2.2	0.9
EPSP	84° 4.19' W		Hole B - Jet-In test	0.3	
to 770 mbsf			Hole C - Re-entry system (20" and 16" casing to 260 mbsf)	3.7	
			Hole C - Drill to 540 mbsf and RCB to 770 mbsf, cement at intervals to stabilize hole;	7.3	1.4
			Log with triple combo, FMS-sonic and VSI		
			Subtotal Days On-Site: 15.8		
			The following sites are alternates to CRIS-13B		
U1379	8° 40.85' N	138	Hole D - Drill to 900 mbsf, RCB core to 1050 mbsf; Log with triple combo, FMS-sonic and VSI	3.9	1.9
EPSP	84° 2.02' W				
to 1050 mbsf					
			Subtotal Days On-Site: 5.8		
CRIS-14A	8° 44.50' N	515	Hole A - APC/XCB to ~800 mbsf; Log with triple combo and FMS-sonic	4.6	1.0
EPSP	84° 9.51' W		Hole B - Drill to 790 mbsf and RCB to 1730 mbsf; Log with triple combo, FMS-sonic and VSI	8.5	1.7
to 1730 mbsf					
			Subtotal Days On-Site: 15.8		
CRIS-15B	8° 42.78' N	689	Hole A - APC/XCB to ~800 mbsf; Log with triple combo and FMS-sonic	4.8	1.0
EPSP	84° 8.77' W		Hole B - Drill to 790 mbsf , RCB to 1500 mbsf; Log with triple combo, FMS-sonic and VSI	7.9	1.7
to 1500 mbsf					
			Subtotal Days On-Site: 15.4		
			This is a contingency site time permitting		
CRIS-20A	8° 57.38' N	100	Hole A - APC to ~100 mbsf	0.5	
EPSP	84° 3.80' W				
to 100 mbsf					
			Subtotal Days On-Site: 0.5		

All advanced piston corer (APC) holes assumed to be cored with nonmagnetic core barrels to overpull limits. All APC holes will be cored using the FlexIt orientation tool. Advanced piston coring temperature tool/sediment temperature tool (APCT-3/SET) temperature measurements will be performed as required to generate a profile for each hole. FMS-sonic = Formation MicroScanner sonic tool string, EPSP = Environmental Protection and Safety Panel, VSI = Versatile Seismic Imager, RCB = rotary core barrel, XCB = extended core barrel.

Figure F1. Topographic and bathymetric map of the Costa Rica area, showing location of the proposed drilling area. Seafloor bathymetry is based on satellite gravimetry and swath mapping (Barckhausen et al., 2001; Fisher et al., 2003; von Huene et al., 2000). Note the collision of Cocos Ridge with the trench offshore the Osa Peninsula. This process brings the seismogenic zone within reach of IODP riser drilling capabilities. DSDP = Deep Sea Drilling Project, ODP = Ocean Drilling Program. Inset shows tectonic setting of Central America, including the plates that interact in this region: North America (NA), Caribbean (CA), South America (SA), Nazca (NZ), Cocos (CO), and Pacific (PA). EPR = East Pacific Rise, CNS = Cocos Nazca spreading center.

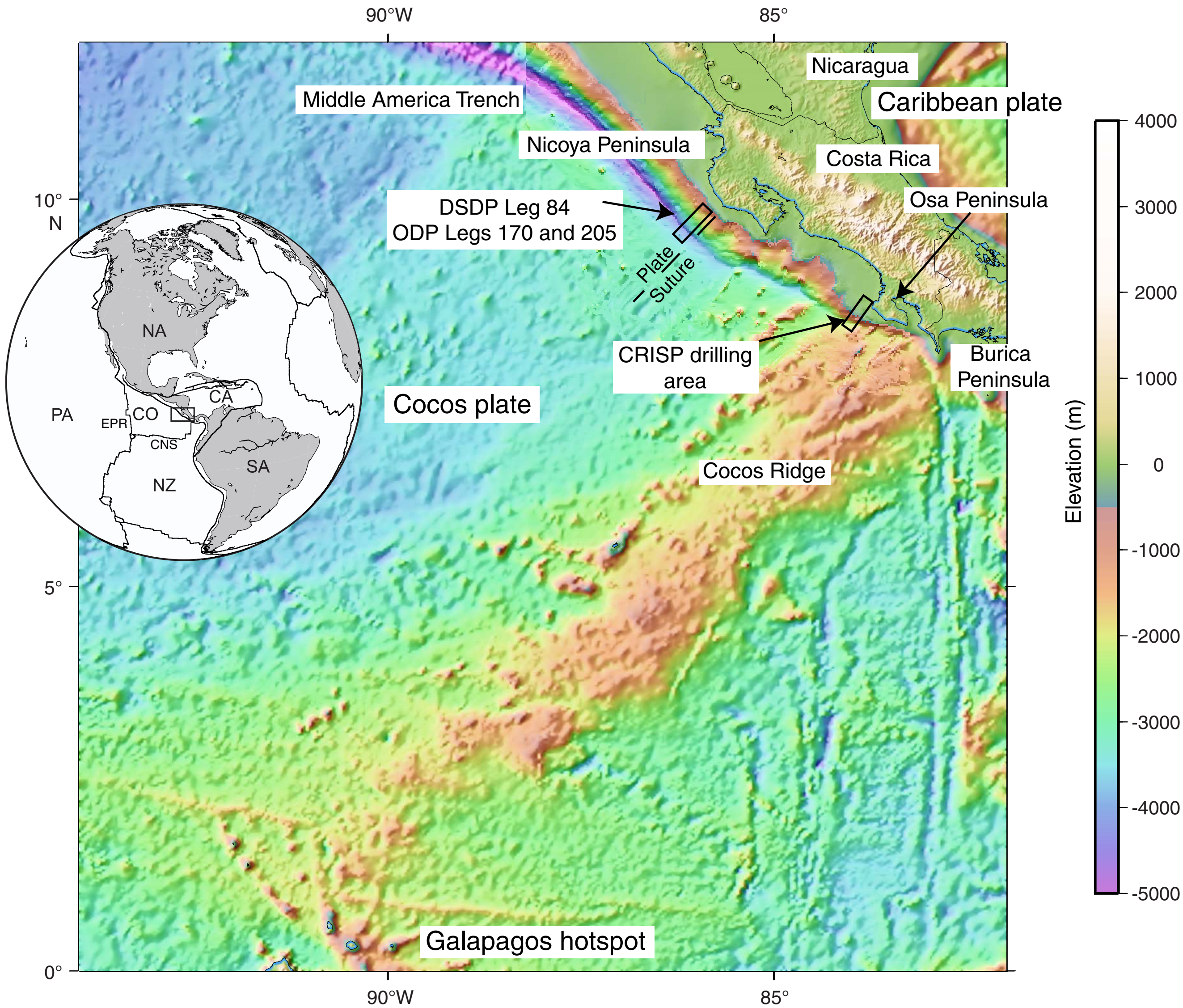


Figure F2. Seismic Line BGR99-7 showing location of Expedition 334 drill sites and the location of proposed CRISP-A2 drilling. Prestack depth migration (C.R. Ranero, unpubl. data) is at a vertical exaggeration of 1.3× (vertical axis is depth). CMP = common midpoint.

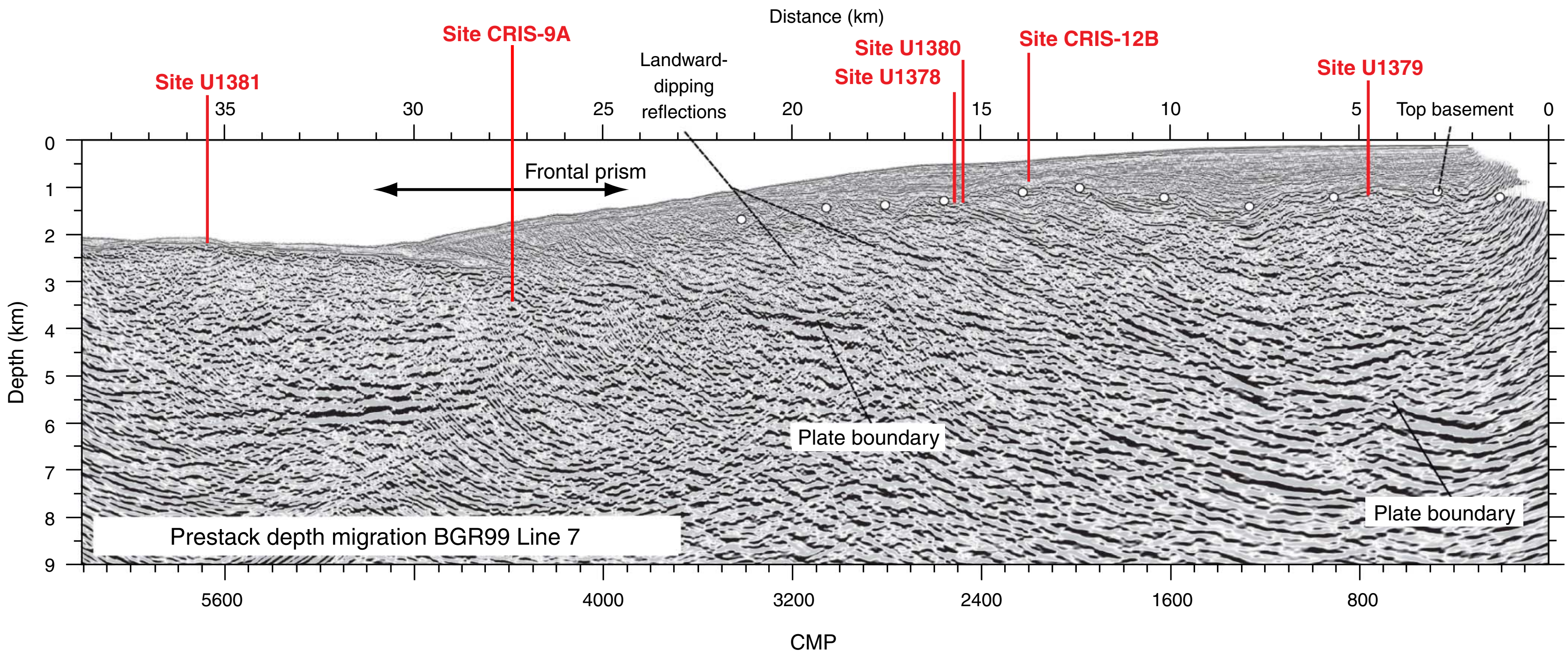


Figure F3. Interpreted wide-angle seismic section from Stavenhagen et al. (1998). Schematic figure through Osa Peninsula margin showing Sites U1381, U1378, U1380, and U1379. VE = vertical exaggeration, v = *P*-wave velocity.

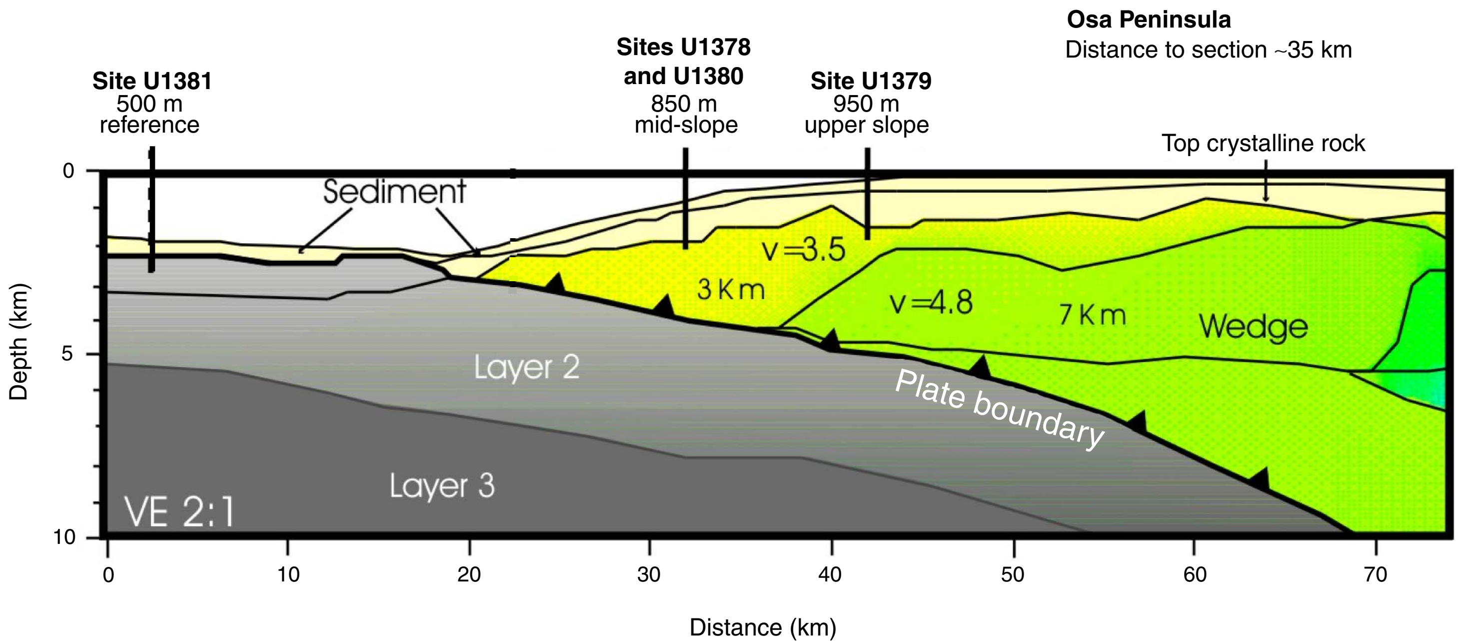


Figure F4. Seismicity along Costa Rica margin. Small black circles show seismicity recorded by Sismologica Nacional (RSN) in the period 1992–2007. Focal mechanisms correspond to large earthquakes (Mw > 6.4) nucleated in the seismogenic zone over the past 25 y. Red circles show aftershocks from the 2002 Osa event, and beige circles show aftershocks from the 1999 Quepos event (Modified from Arroyo et al., 2011).

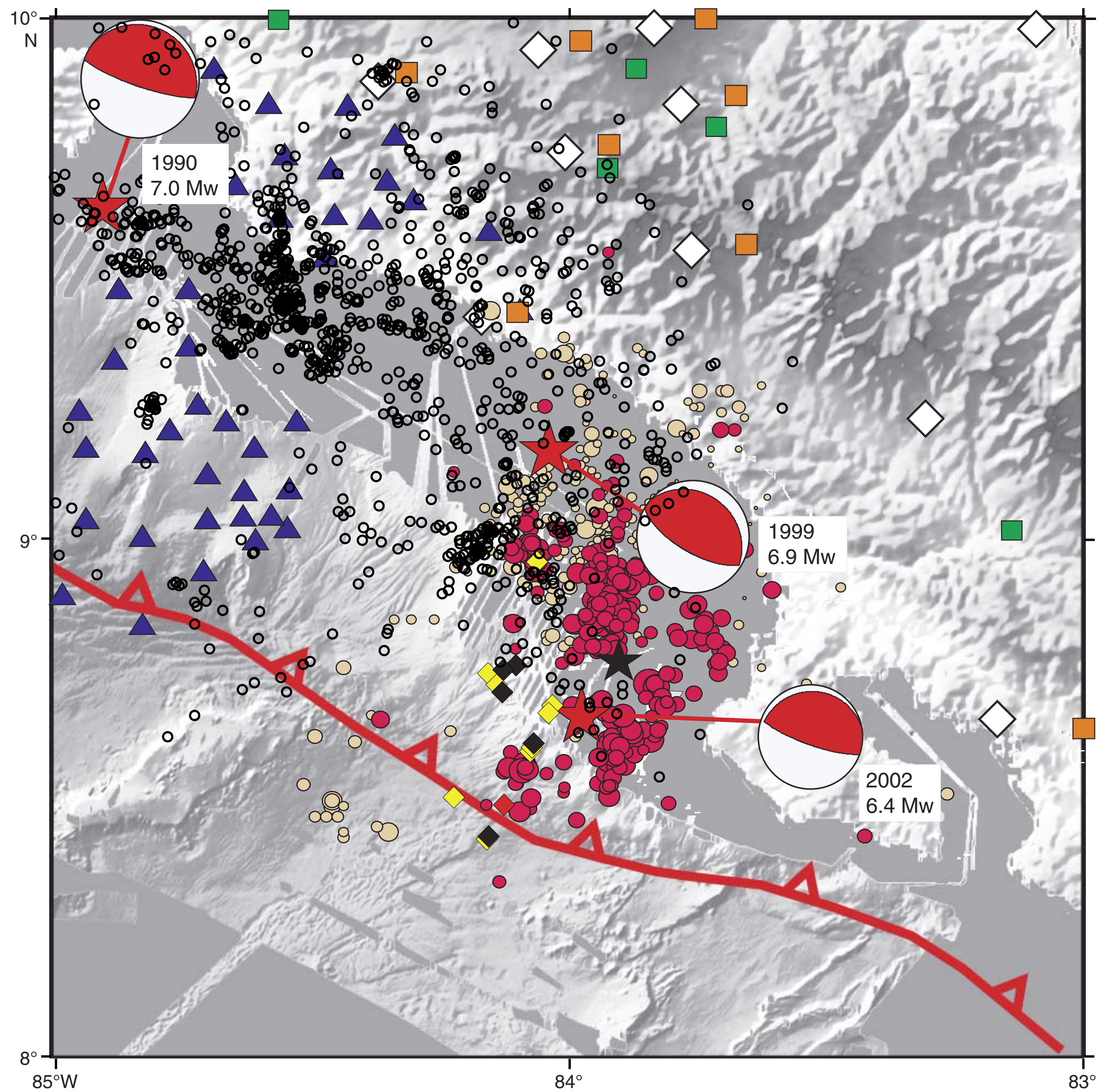


Figure F5. Central America Focus Site activity map (2008; **media.marine-geo.org/image/central-america-focus-site-activity-map-2008-0/**). SEIZE = Seismogenic Zone Experiment, OBS = ocean-bottom seismometers, TUCAN = Tomography Under Costa Rica and Nicaragua, ODP = Ocean Drilling Program, CORKs = circulation obviation retrofit kits, 3D = three-dimensional, IODP = Integrated Ocean Drilling Program, MCS = multichannel seismic, CRISP = Costa Rica Seismogenesis Project.

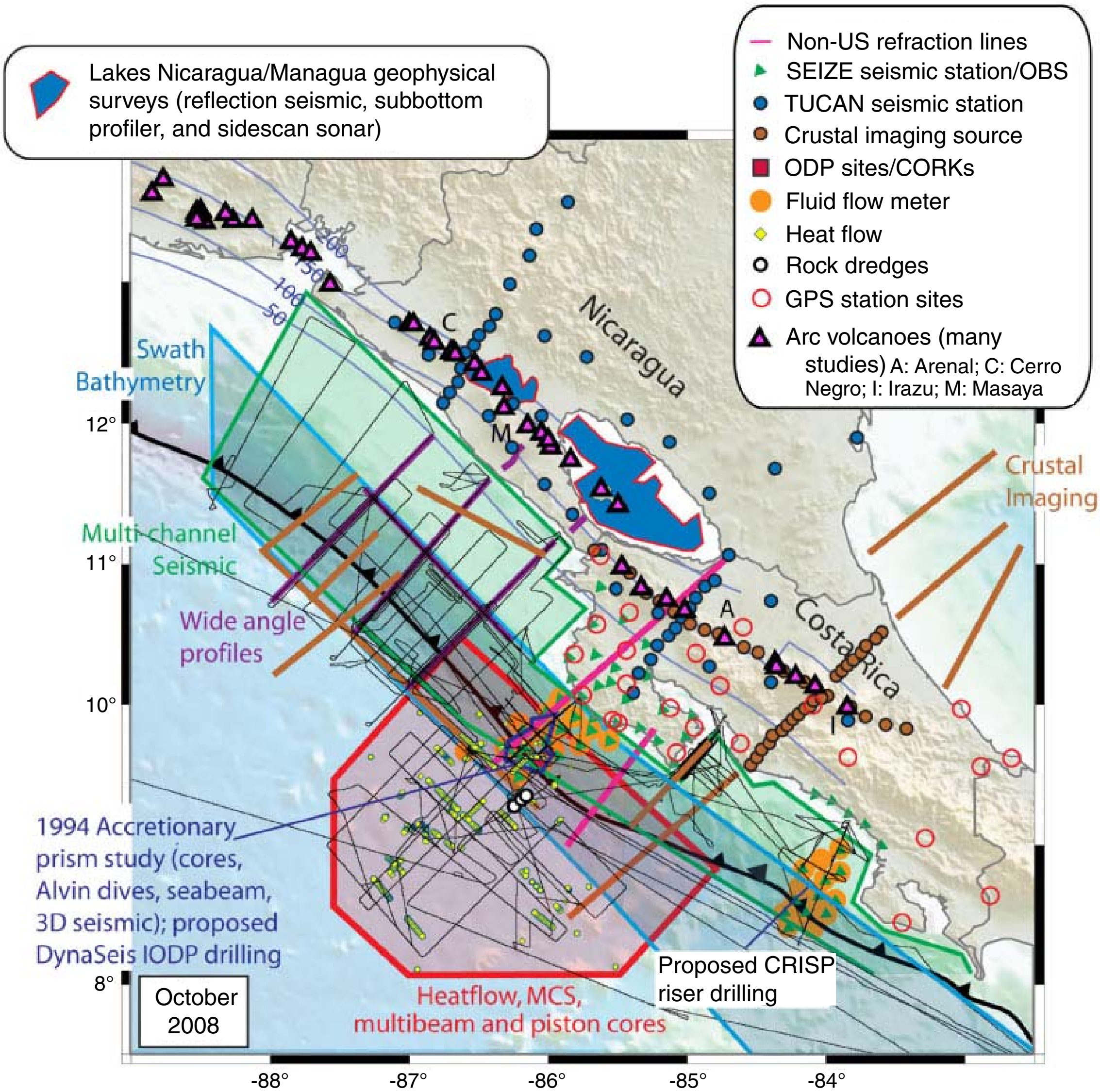


Figure F6. Location of proposed drill sites. Red diamonds denote primary sites (U1381, CRIS-9A, U1380, and CRIS-13B) and yellow diamonds denote alternate and contingency sites (U1378, CRIS-12B, U1379, CRIS-14A, CRIS-15B, CRIS-19A, and CRIS-20A). Small black circles show seismicity recorded by Sismologica Nacional (RSN) in the period 1992–2007. Red circles show aftershocks from the 2002 Osa event, and beige circles show aftershocks from the 1999 Quepos event. Red lines = 3-D seismic survey, black lines = seismic reflection lines, blue circles = xbt drops. The numbers along the short and long axis of the 3-D survey represent inlines and xlines, respectively. (Figure shown on next page.)

Figure F6 (continued). (Caption shown on previous page.)

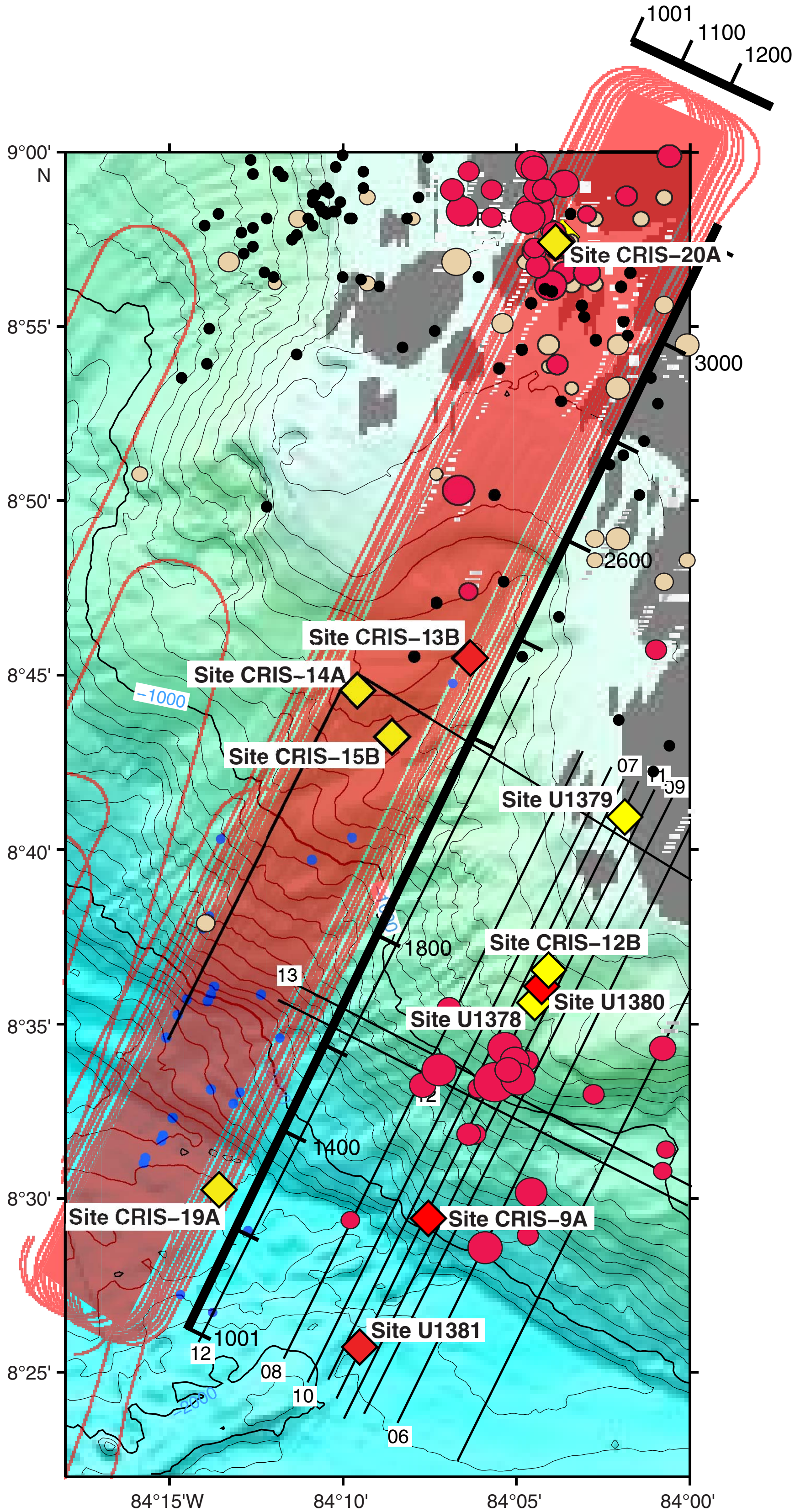


Figure F7. Heat flow data offshore Costa Rica. Color-coded circles indicate heat-flow values (von Herzen and Uyeda, 1963; Vacquier et al., 1967; Langseth and Silver, 1996; Fisher et al., 2003; Hutnak et al., 2007; Harris et al., 2010a). Stars show location of drill sites. Dashed red line indicates position of the thermal transition between areas of relatively low and high heat flow. EPR-generated crust to the north of the triple junction and fracture zone traces has heat flow suppressed by roughly 70%, whereas CNS-generated crust to the south generally has heat flow that matches conductive lithospheric cooling models (Hutnak et al., 2007, 2008).

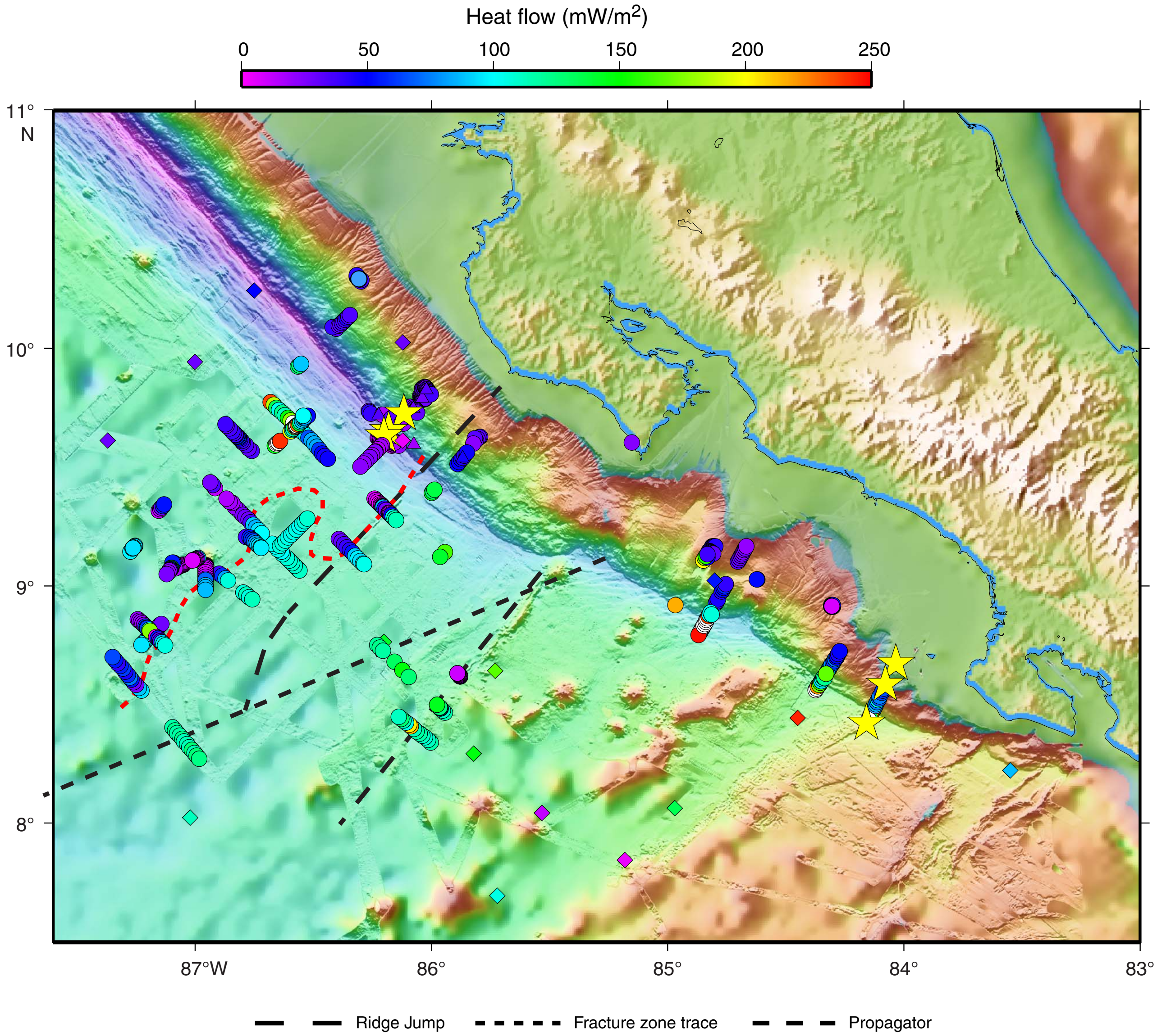


Figure F8A. Summary of lithostratigraphic, physical property, and geochemical data obtained onboard, Hole U1378B (Expedition 334 Scientists, 2011). **A.** 0–280 mbsf. (Continued on next page.)

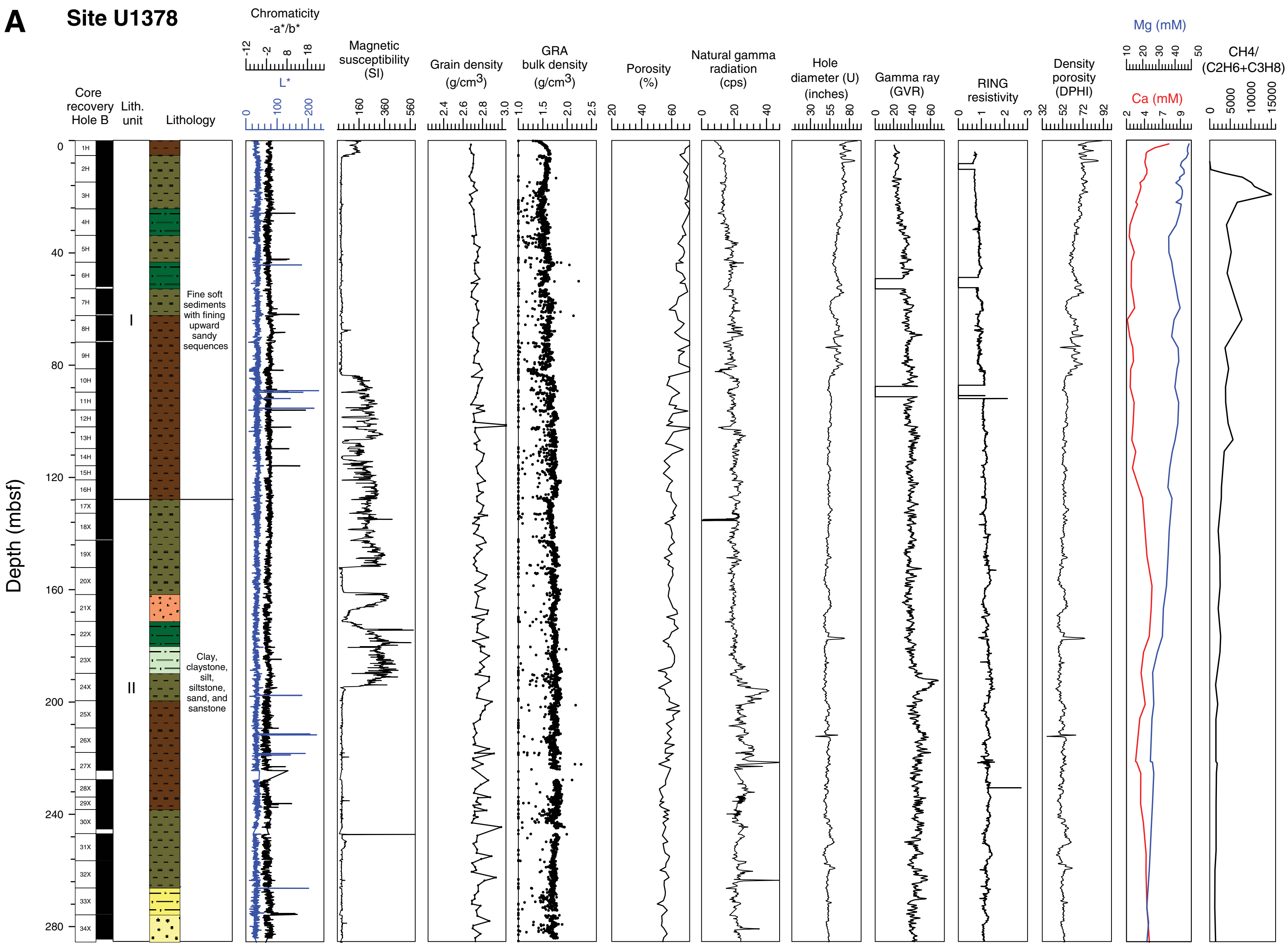


Figure F8B (continued). **B.** 280–520 mbsf.

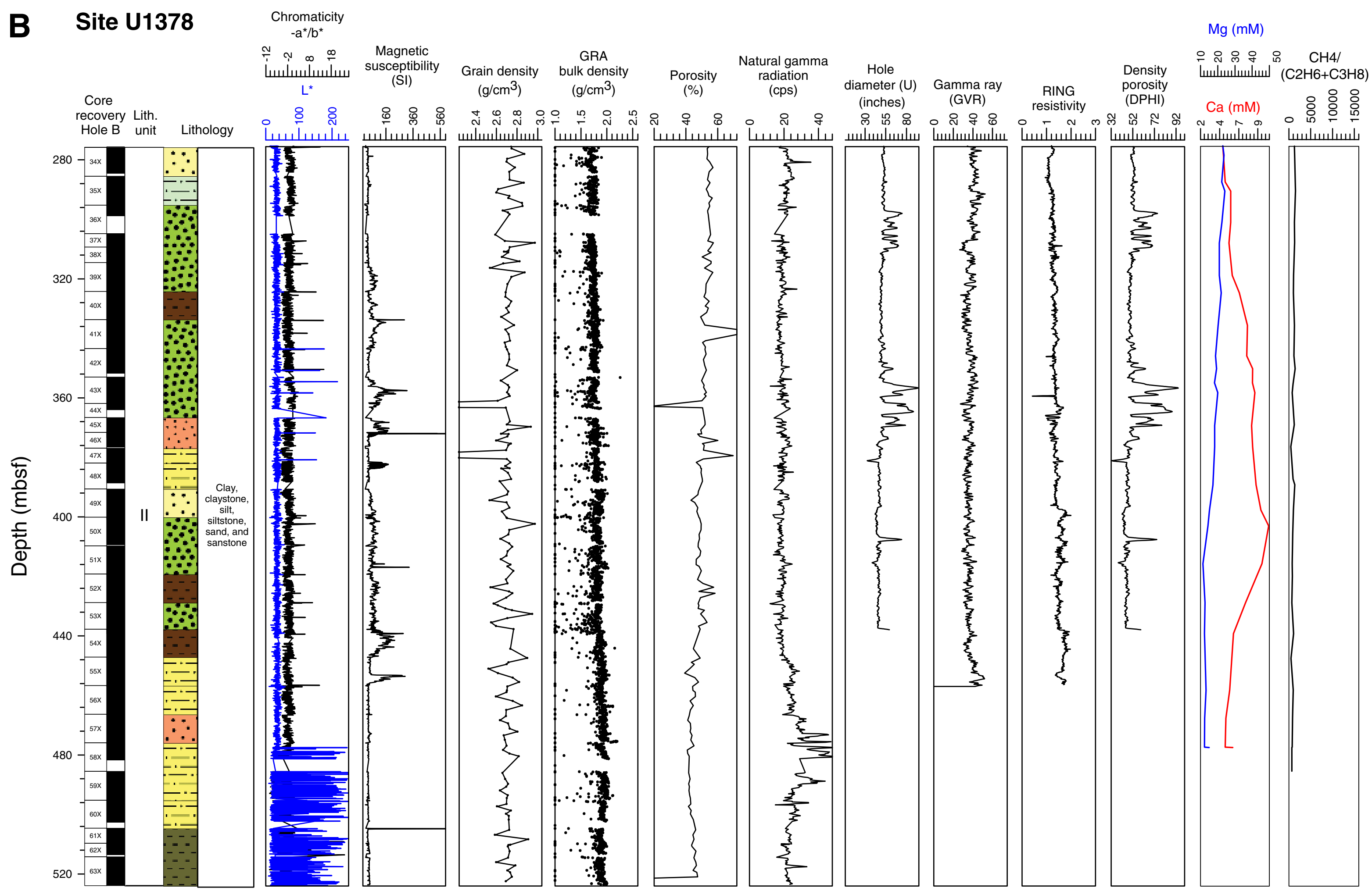


Figure F9A. Summary of lithostratigraphic, physical property, and geochemical data obtained onboard, Hole U1379C (Expedition 334 Scientists, 2011). **A.** 0–400 mbsf. (Continued on next page.)

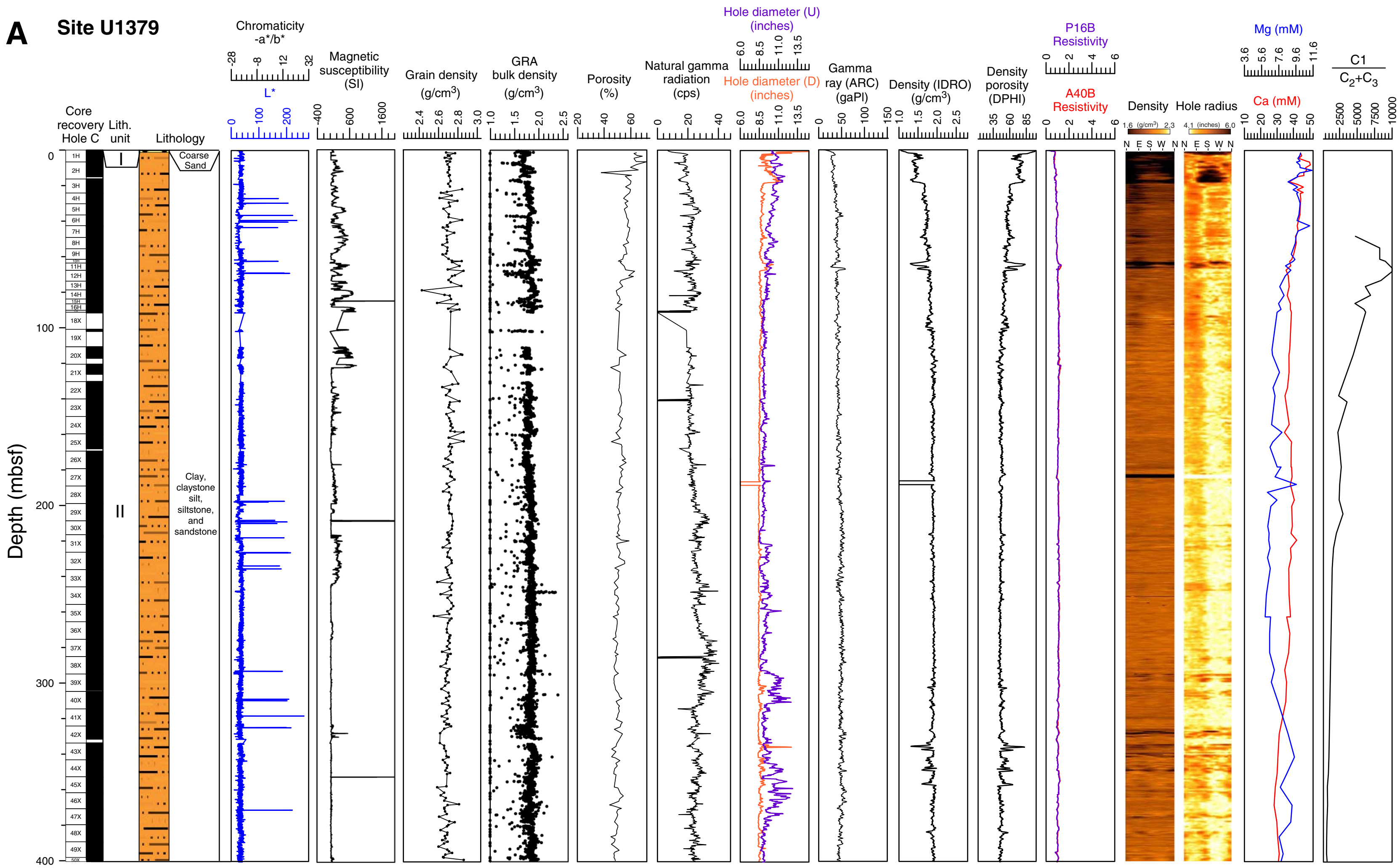


Figure F9B (continued). B. 400–900 mbsf (Expedition 334 Scientists, 2011).

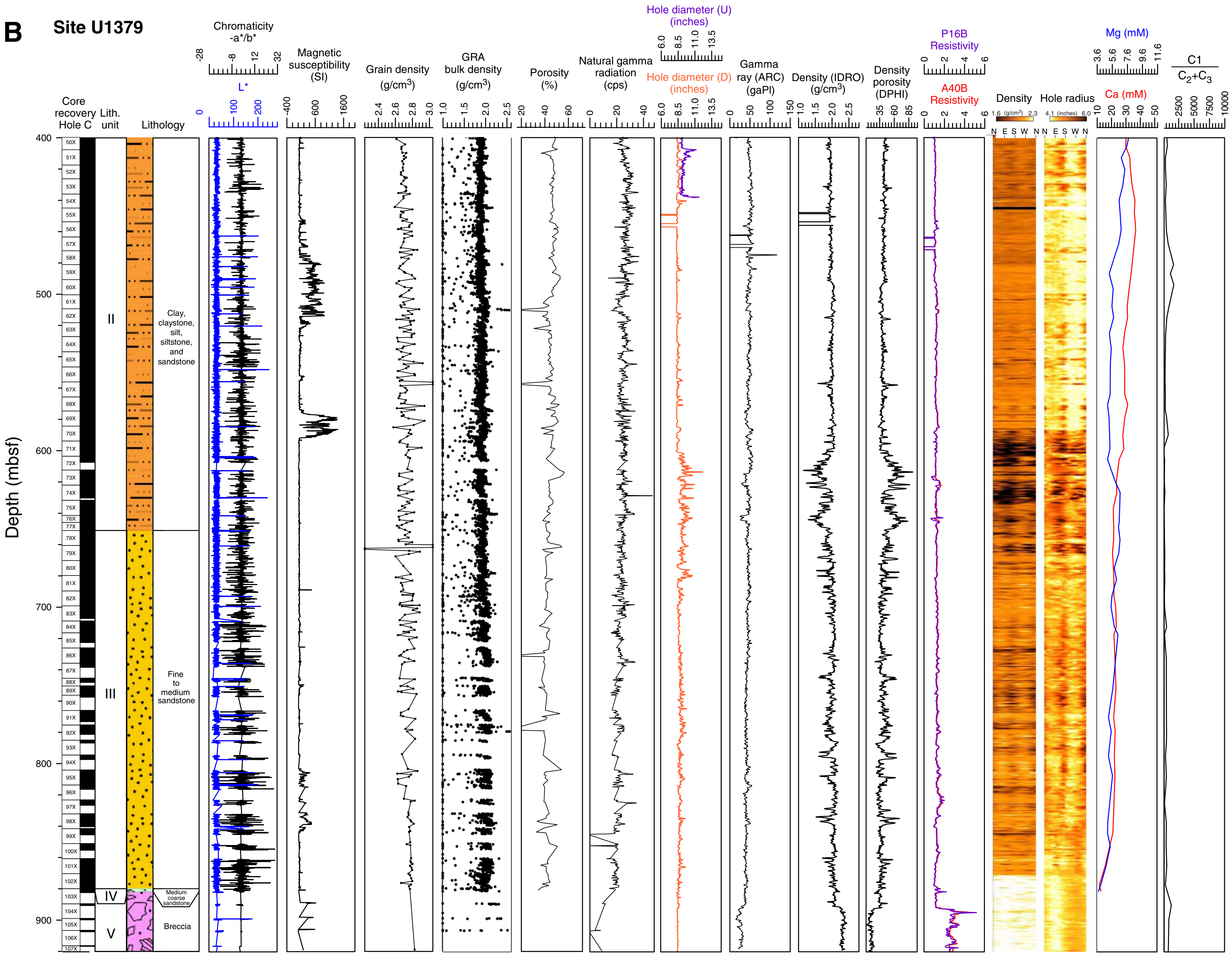


Figure F10. Summary of lithostratigraphy, physical property, and geochemical data obtained onboard, Hole U1381A (Expedition 334 Scientists, 2011).

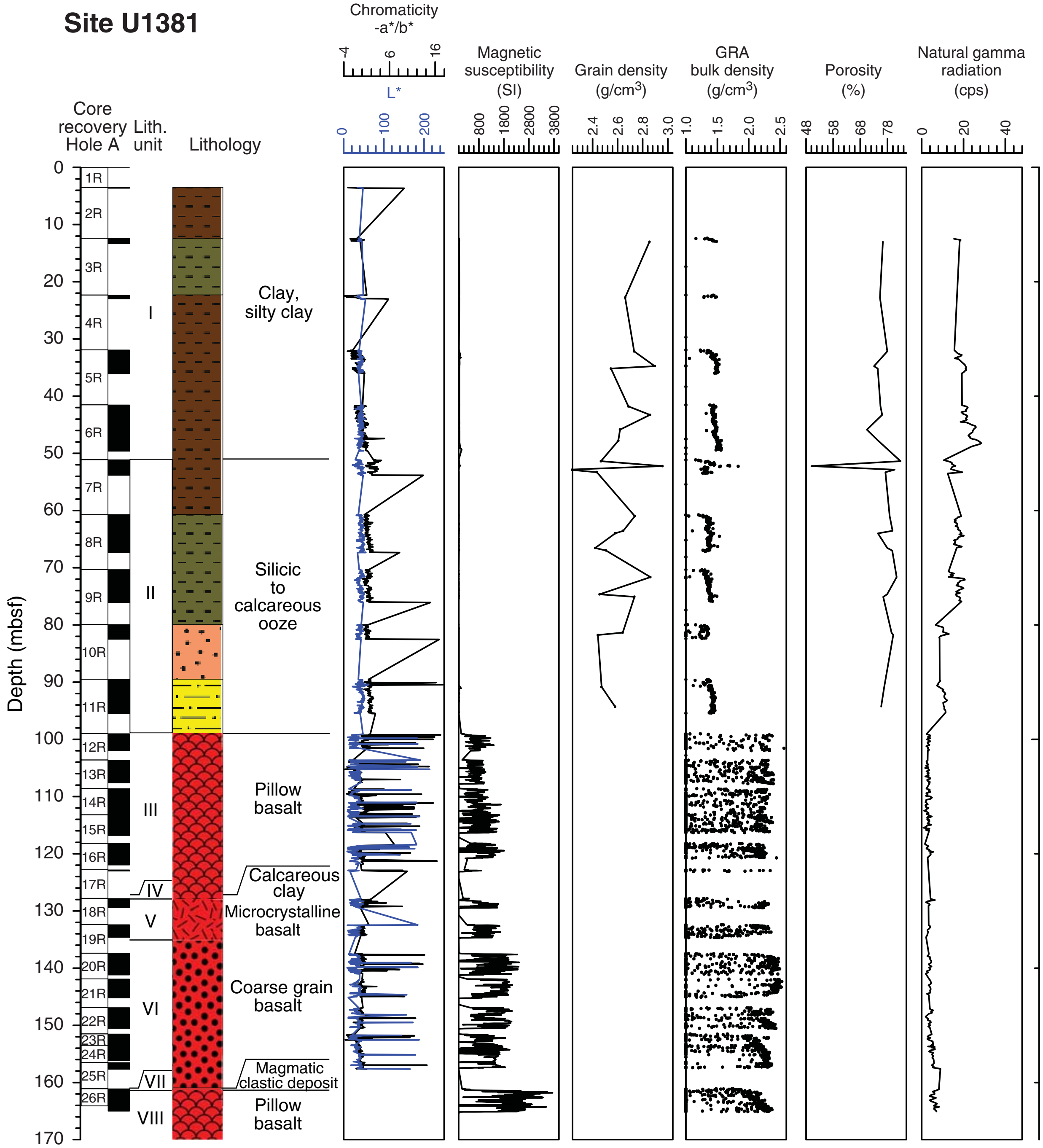
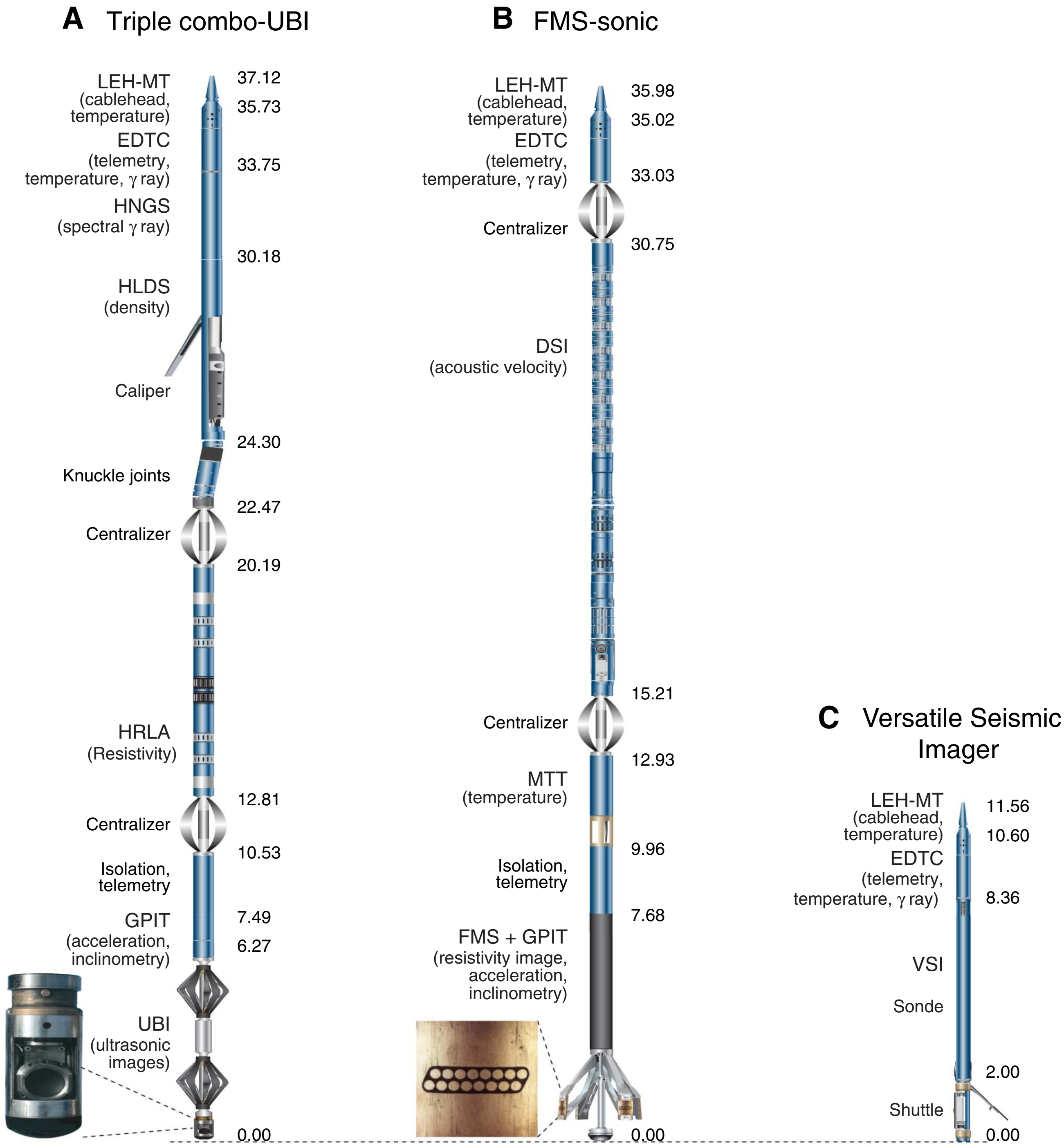


Figure F11. Wireline tool strings to be deployed at the Expedition 344 sites. **A.** Triple combo-UBI tool string takes downhole measurements of hole diameter, natural gamma ray, bulk density, electrical resistivity, and ultrasonic images of the borehole. **B.** FMS-sonic tool string measures borehole resistivity images, natural gamma ray, and *P*- and *S*-wave velocities. **C.** VSI tool string acquires seismic waveform data in a check shot experiment. LEH-MT = logging equipment head-mud temperature, EDTC = Enhanced Digital Telemetry Cartridge, HNGS = Hostile Environment Natural Gamma Ray Sonde, HLDS = Hostile Environment Litho-Density Sonde, HRLA = High-Resolution Laterolog Array, GPIT = General Purpose Inclinometry Tool, UBI = Ultrasonic Borehole Imager, DSI = Dipole Sonic Imager, MTT = Modular Temperature Tool, FMS = Formation MicroScanner, VSI = Versatile Seismic Imager. Except for MTT, all acronyms are marks of Schlumberger.



Site summaries

Site U1381 (Proposed Site CRIS-1A)

Priority:	Primary
Position:	8°25.71474′N, 84°9.47028′W
Water depth (m):	2069
Target drilling depth (mbsf):	100
Approved maximum penetration (mbsf):	350
Survey coverage:	Line BGR 99-7 common midpoint (CMP) 5740 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF2**) • Location map (Fig. **F6**)
Objective:	Characterize oceanic input to the subduction zone.
Drilling, coring, and downhole measurements program:	• Hole C: APC to 100 mbsf. • Formation temperature measurements (APCT-3). • FlexIt core orientation measurements.
Nature of rock anticipated:	Sediments: mud, silt, and basaltic flows.

Site summaries (continued)

Proposed Site CRIS-19A

Priority:	Alternate
Position:	8°30.22794′N, 84°13.52556′W
Water depth (m):	2457
Target drilling depth (mbsf):	400
Approved maximum penetration (mbsf):	500
Survey coverage:	Inline 1225, Xline 1040 • Track map (Fig. AF1) • Seismic profile (Fig. AF3) • Location map (Fig. F6)
Objective:	Alternate for U1381. Characterize oceanic input to the subduction zone.
Drilling, coring, and downhole measurements program:	• Hole A: APC to basement. • Formation temperature measurements (APCT-3). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic).
Nature of rock anticipated:	Sediments: mud, silt, and basaltic flows.

Site summaries (continued)

Site U1380 (Proposed Site CRIS-10A)

Priority:	Primary
Position:	8°35.99802′N, 84°4.4037′W
Water depth (m):	504
Target drilling depth (mbsf):	800 (550 m sediment, 250 m basement)
Approved maximum penetration (mbsf):	800
Survey coverage:	Line BGR 99-7 CMP 2350 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF4**) • Location map (Fig. **F6**)
Objective:	Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole B: jet-in test for reentry system. • Hole C: reentry system (20 and 16 inch casing to 260 mbsf). • Hole C: drill without recovery to 300 mbsf, RCB from 300 to 800 mbsf. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Site U1378 (Proposed Site CRIS-3B)

Priority:	Alternate
Position:	8°35.54136′N, 84°4.63062′W
Water depth (m):	522
Target drilling depth (mbsf):	1000 (890 m sediment, 110 m basement)
Approved maximum penetration (mbsf):	1000
Survey coverage:	Line BGR 99-7 CMP 2500 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF4**) • Location map (Fig. **F6**)
Objective:	Alternate for U1380. Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole C: jet-in test for reentry system. • Hole D: reentry system (20 and 16 inch casing to 260 mbsf). • Hole D: drill without recovery to 450 mbsf, RCB from 450 to 1000 mbsf. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Proposed Site CRIS-12B

Priority:	Alternate
Position:	8°36.45438′N, 84°4.18578′W
Water depth (m):	430
Target drilling depth (mbsf):	770 (550 m sediment, 220 m basement)
Approved maximum penetration (mbsf):	770
Survey coverage:	Line BGR 99-7 CMP 2200 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF4**) • Location map (Fig. **F6**)
Objective:	Alternate for Site U1380. Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole A: APC to 550 mbsf. • Hole B: jet-in test for reentry system. • Hole C: reentry system (20 and 16 inch casing to 260 mbsf). • Hole C: drill without recovery to 540 mbsf, RCB to 770 mbsf. • Formation temperature measurements (APCT-3/SET). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Proposed Site CRIS-9A

Priority:	Primary
Position:	8°29.3274′N, 84°7.69308′W
Water depth (m):	2000
Target drilling depth (mbsf):	980 (780 m sediment, 200 m basement)
Approved maximum penetration (mbsf):	980
Survey coverage:	Line BGR 99-7 CMP 4550 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF5**) • Location map (Fig. **F6**)
Objective:	Penetration of décollement at shallow level, fluid flow regime, oceanic crust.
Drilling, coring, and downhole measurements program:	• Hole A: APC/XCB to 500 mbsf. • Hole B: drill without recovery to 490 mbsf, RCB from 490 to 980 mbsf. • Formation temperature measurements (APCT-3/SET). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia, and basaltic flows.

Site summaries (continued)

Proposed Site CRIS-13B

Priority:	Primary
Position:	8°44.46177′N, 84° 6.81293′W
Water depth (m):	543
Target drilling depth (mbsf):	1430 (1330 m sediment, 100 m basement)
Approved maximum penetration (mbsf):	1430
Survey coverage:	Inline 1209, Xline 2200 • Track map (Fig. AF1) • Seismic profile (Fig. AF6) • Location map (Fig. F6)
Objective:	Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole A: APC/XCB to 600 mbsf. • Hole B: drill without recovery to 590 mbsf, RCB from 590 to 1430 mbsf. • Formation temperature measurements (APCT-3/SET). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Site U1379 (Proposed Site CRIS-4A)

Priority:	Alternate
Position:	8°40.84962′N, 84°2.01690′W
Water depth (m):	127
Target drilling depth (mbsf):	1050 (850 m sediment, 200 m basement)
Approved maximum penetration (mbsf):	1050
Survey coverage:	Line BGR 99-7 CMP 750 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF7**) • Location map (Fig. **F6**)
Objective:	Alternate to CRIS-13B. Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole D: drill without recovery to 900 mbsf, RCB from 900 to 1050 mbsf. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Proposed Site CRIS-14A

Priority:	Alternate
Position:	8°44.50272′N, 84°9.50544′W
Water depth (m):	504
Target drilling depth (mbsf):	1730 (1630 m sediment, 100 m basement)
Approved maximum penetration (mbsf):	1730
Survey coverage:	Inline 1090, Xline 2115 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF8**) • Location map (Fig. **F6**)
Objective:	Alternate to CRIS-13B. Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole A: APC/XCB to 800 mbsf. • Hole B: drill without recovery to 790 mbsf, RCB from 790 to 1730 mbsf. • Formation temperature measurements (APCT-3/SET). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Proposed Site CRIS-15B

Priority:	Alternate
Position:	8°42.77840′N, 84° 8.76753′W
Water depth (m):	678
Target drilling depth (mbsf):	1500 (1425 m sediment, 75 m basement)
Approved maximum penetration (mbsf):	1500
Survey coverage:	Inline 1160, Xline 2025 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF9**) • Location map (Fig. **F6**)
Objective:	Alternate for CRIS-13B. Characterize upper plate basement and fluid flow.
Drilling, coring, and downhole measurements program:	• Hole A: APC/XCB to 800 mbsf. • Hole B: drill without recovery to 790 mbsf, RCB from 790 to 1500 mbsf. • Formation temperature measurements (APCT-3/SET). • FlexIt core orientation measurements. • Wireline logging (triple combo-UBI, FMS-sonic, VSI).
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia. Basement: shaly matrix breccia with carbonate, cherty, and basaltic clasts.

Site summaries (continued)

Proposed Site CRIS-20A

Priority:	Contingency
Position:	8°57.381′N, 84°3.796′W
Water depth (m):	89
Target drilling depth (mbsf):	100
Approved maximum penetration (mbsf):	100
Survey coverage:	Inline 1057, Xline 2945 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF10**) • Location map (Fig. **F6**)
Objective:	Characterize sediments to correlate with 3-D seismic stratigraphy.
Drilling, coring, and downhole measurements program:	• APC to refusal. • Formation temperature measurements (APCT-3). • FlexIt core orientation measurements.
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia.

Figure AF1. Track map for proposed primary and alternate Expedition 344 sites. **A.** Black lines = seismic reflection BGR99 profiles, red line = BGR99-7.(Continued on next page.)

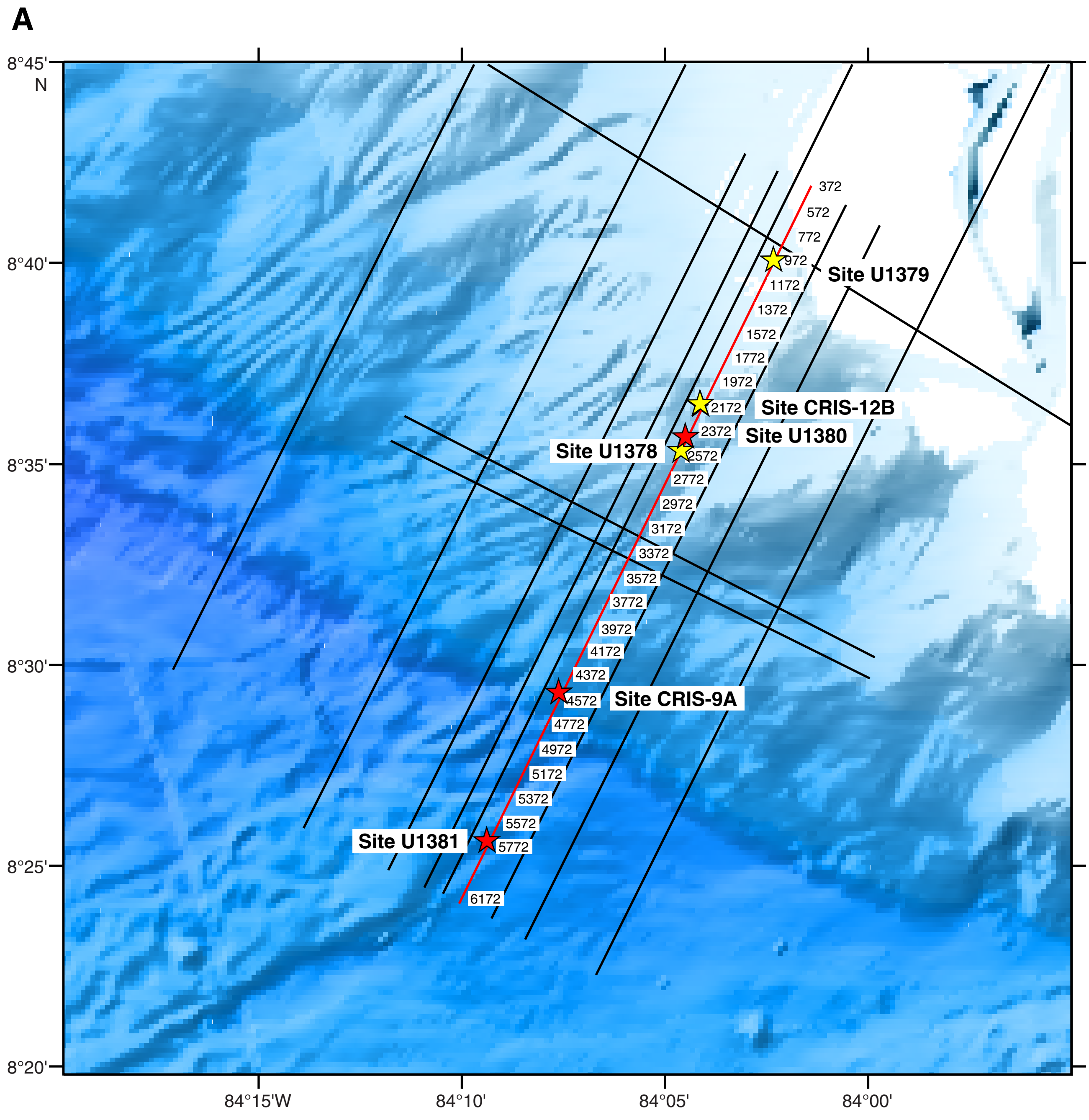


Figure AF1 (continued). B. Map of MGL1106 3-D seismic survey with proposed CRISP sites. Red diamonds = primary sites, yellow diamonds = alternate sites, red lines = 3-D seismic survey, black lines = seismic reflection lines (see Fig. AF1A), blue circles = xbt drops. The numbers along the short and long axis of the 3-D survey represent inlines and xlines, respectively. (Figure shown on next page.)

Figure AF1 (continued). (Caption shown on previous page.)

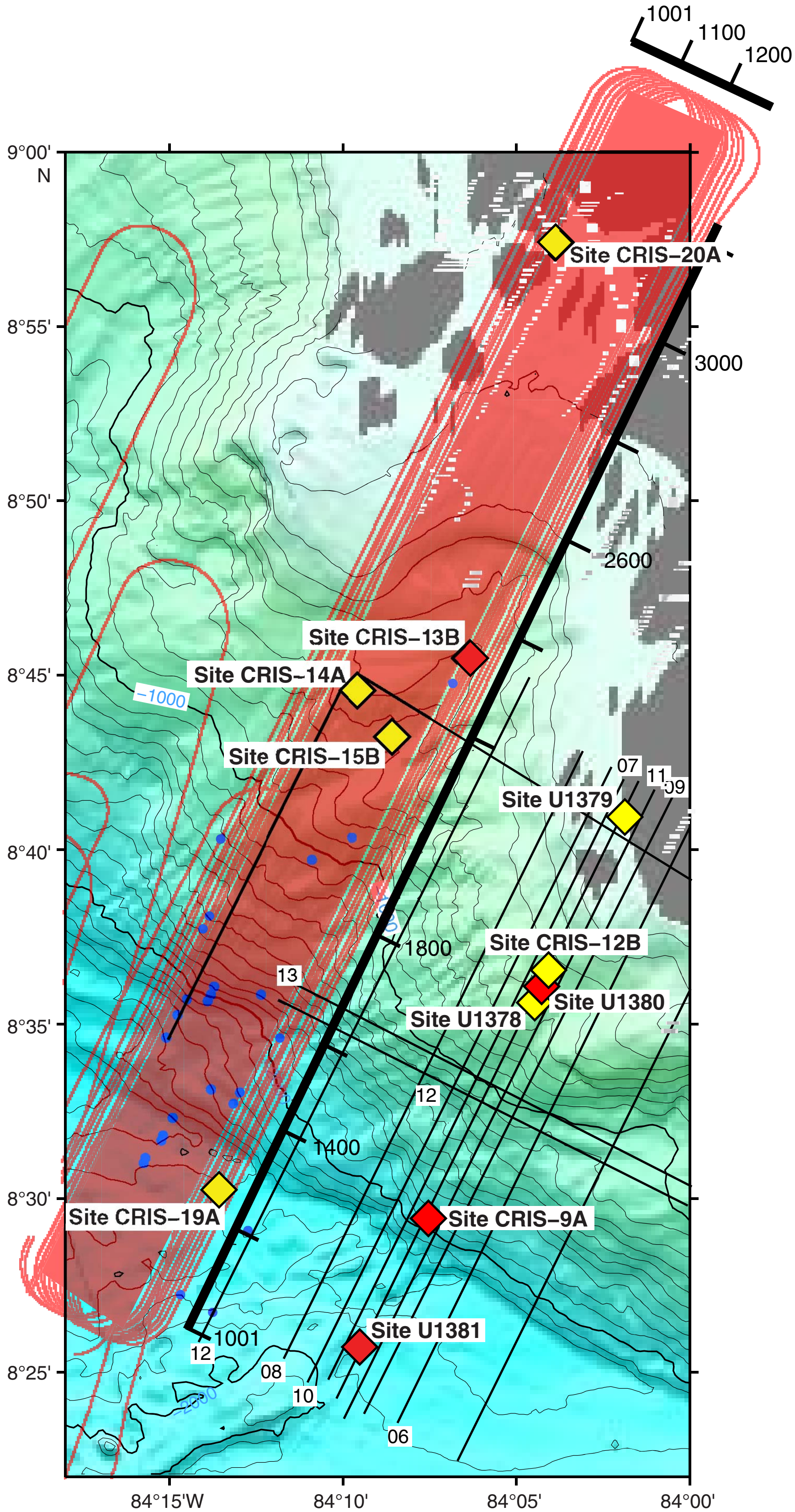


Figure AF2. Proposed primary Site U1381 (CRIS-1A; Line BGR99-7, CMP 5740). CMP = common midpoint. (Site CRIS-7A is not part of this expedition.)

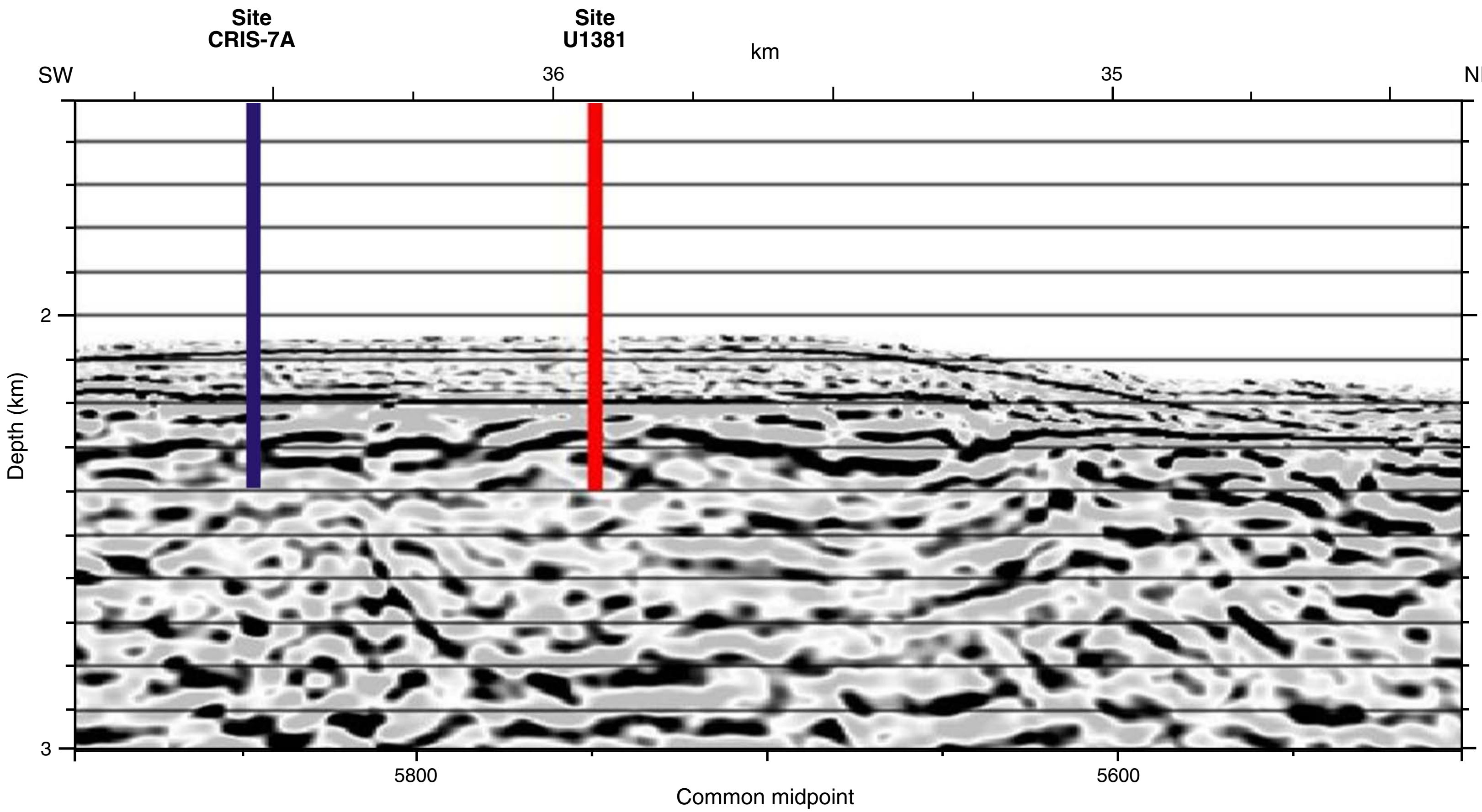


Figure AF3. Proposed alternate Site CRIS-19A (Inline 1225, XLine 1040).

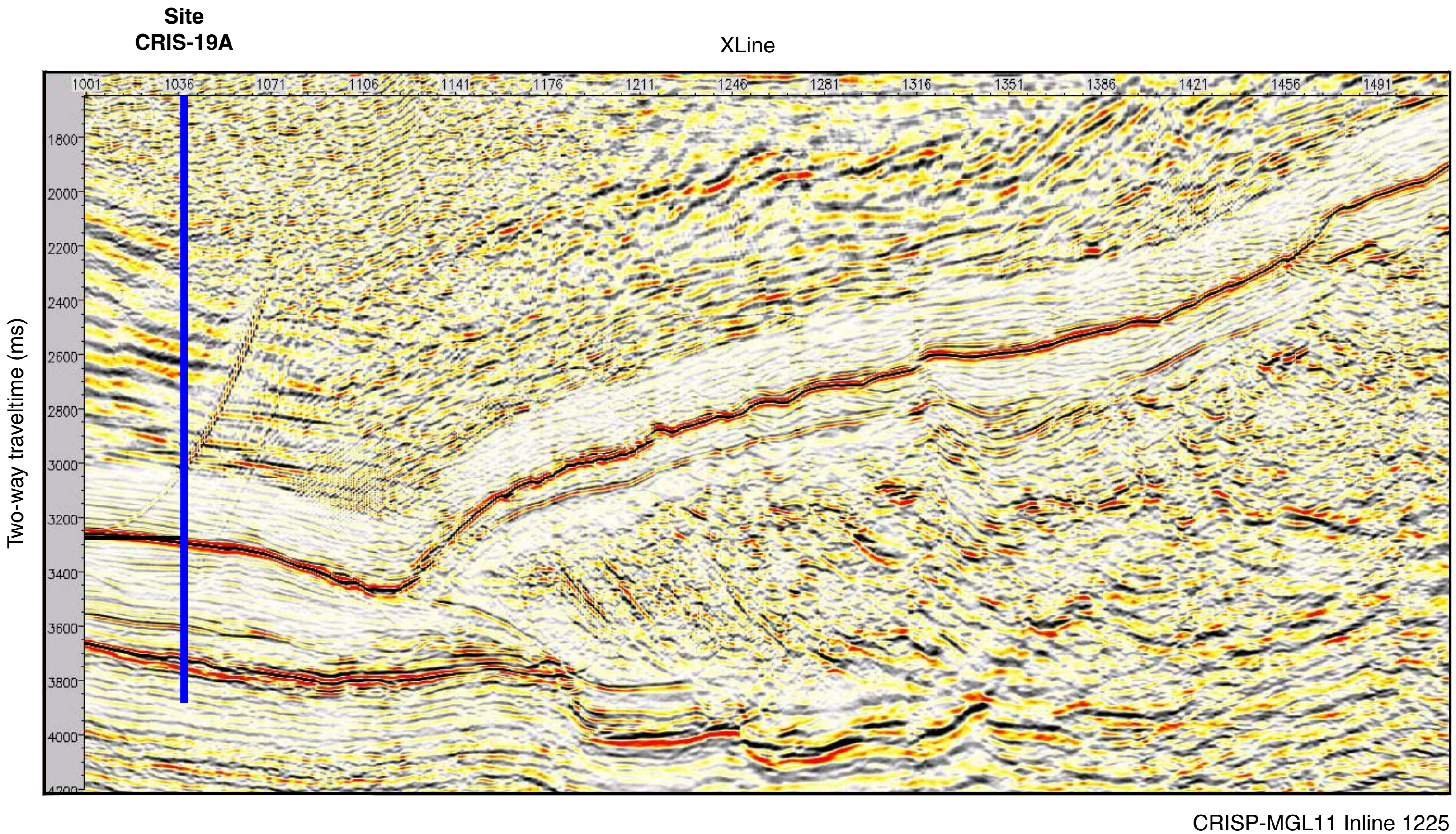


Figure AF4. Proposed primary Site U1380 (CRIS-10A; Line BGR99-7, CMP 2350) and alternate Sites U1378 (CRIS-3B; CMP 2500) and CRIS-12B (CMP 2200). CMP = common midpoint.

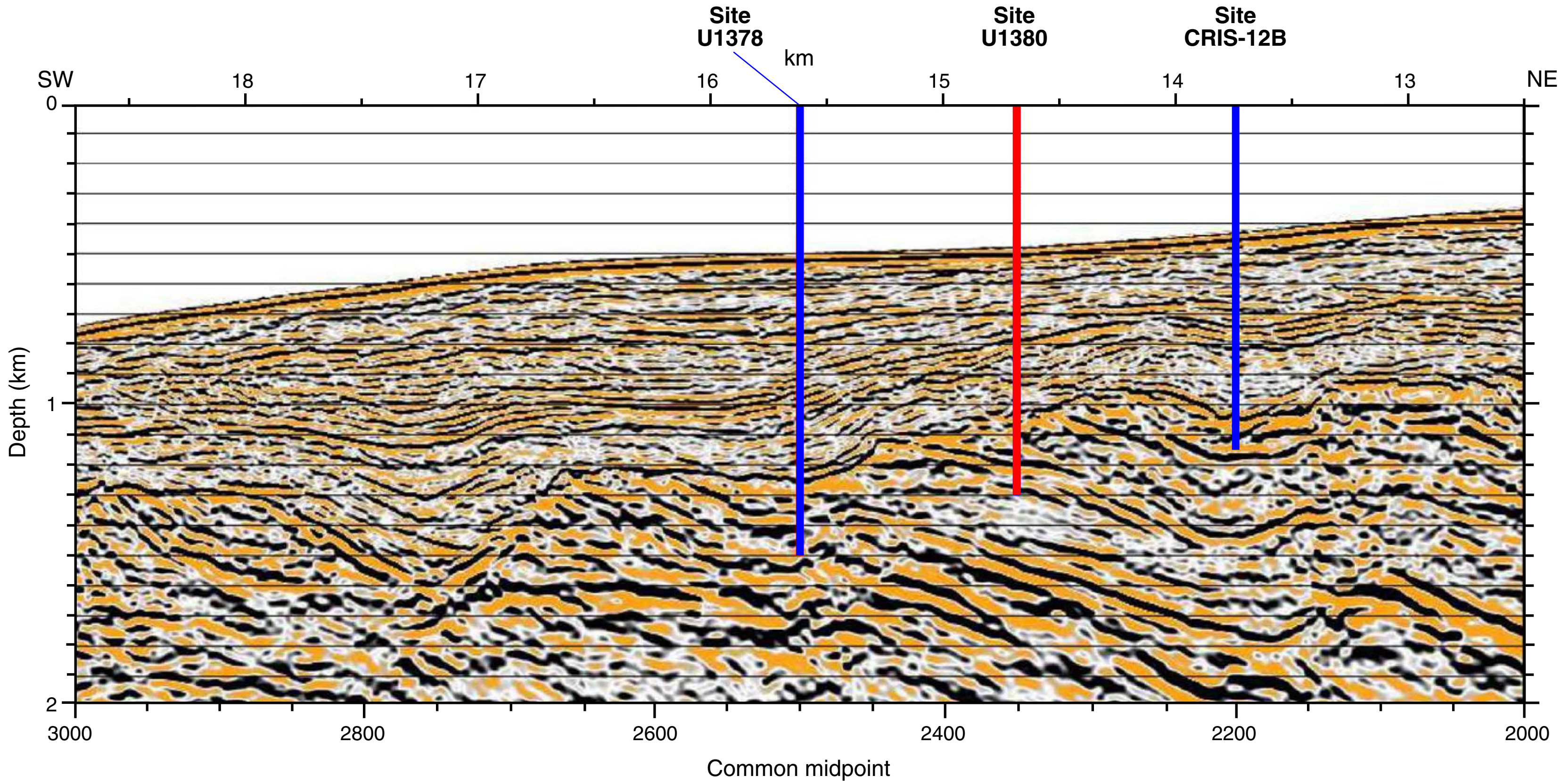


Figure AF5. Proposed primary Site CRIS-9A (Line BGR99-7, CMP 4550). CMP = common midpoint. (Site CRIS-2B is not part of this expedition.)

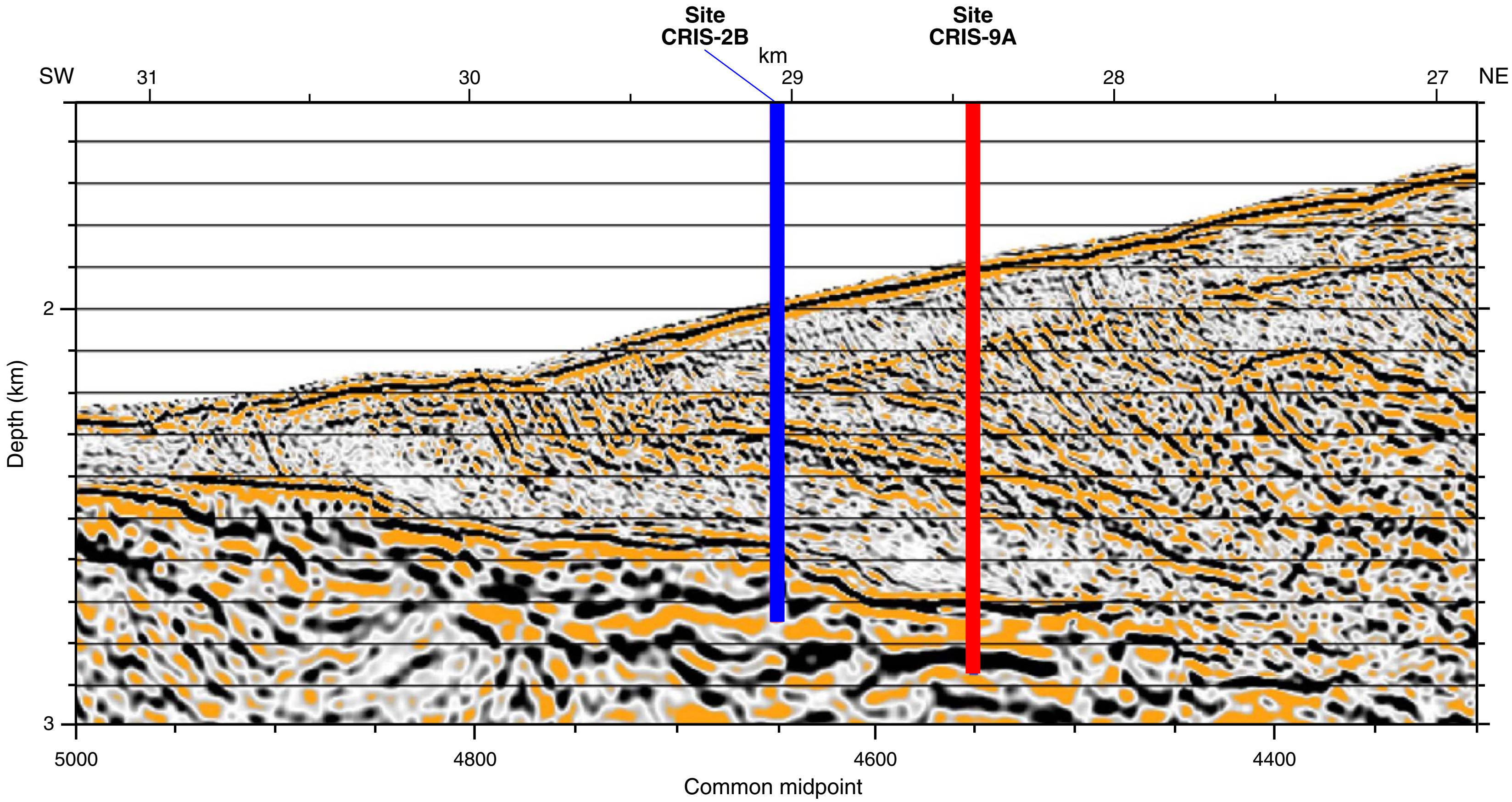


Figure AF6. Proposed primary Site CRIS-13B (Inline 1209, XLine 2200).

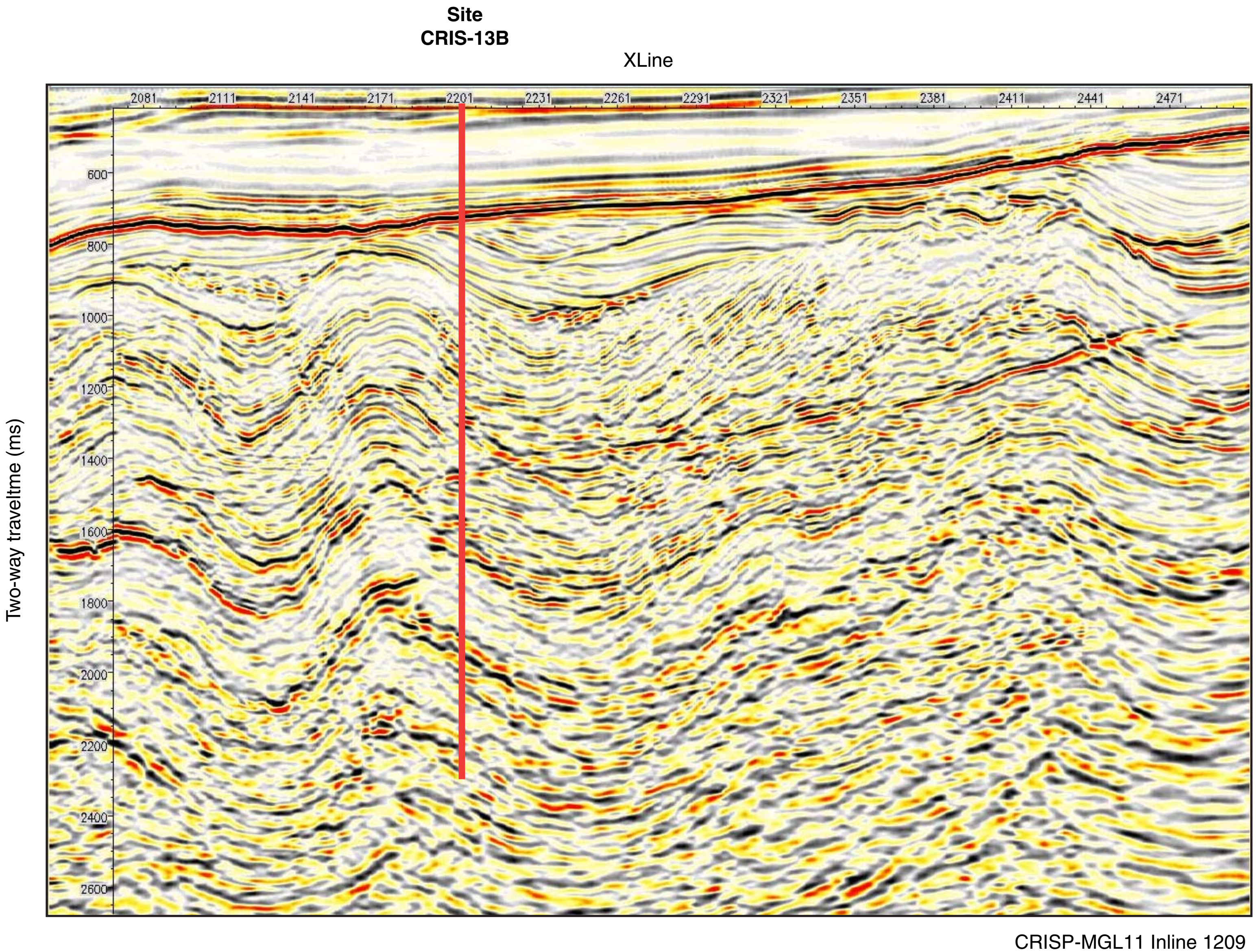


Figure AF7. Proposed alternate Site U1379 (CRIS-4A; Line BGR99-7, CMP 750). CMP = common midpoint. (Site CRIS-11A is not part of this expedition.)

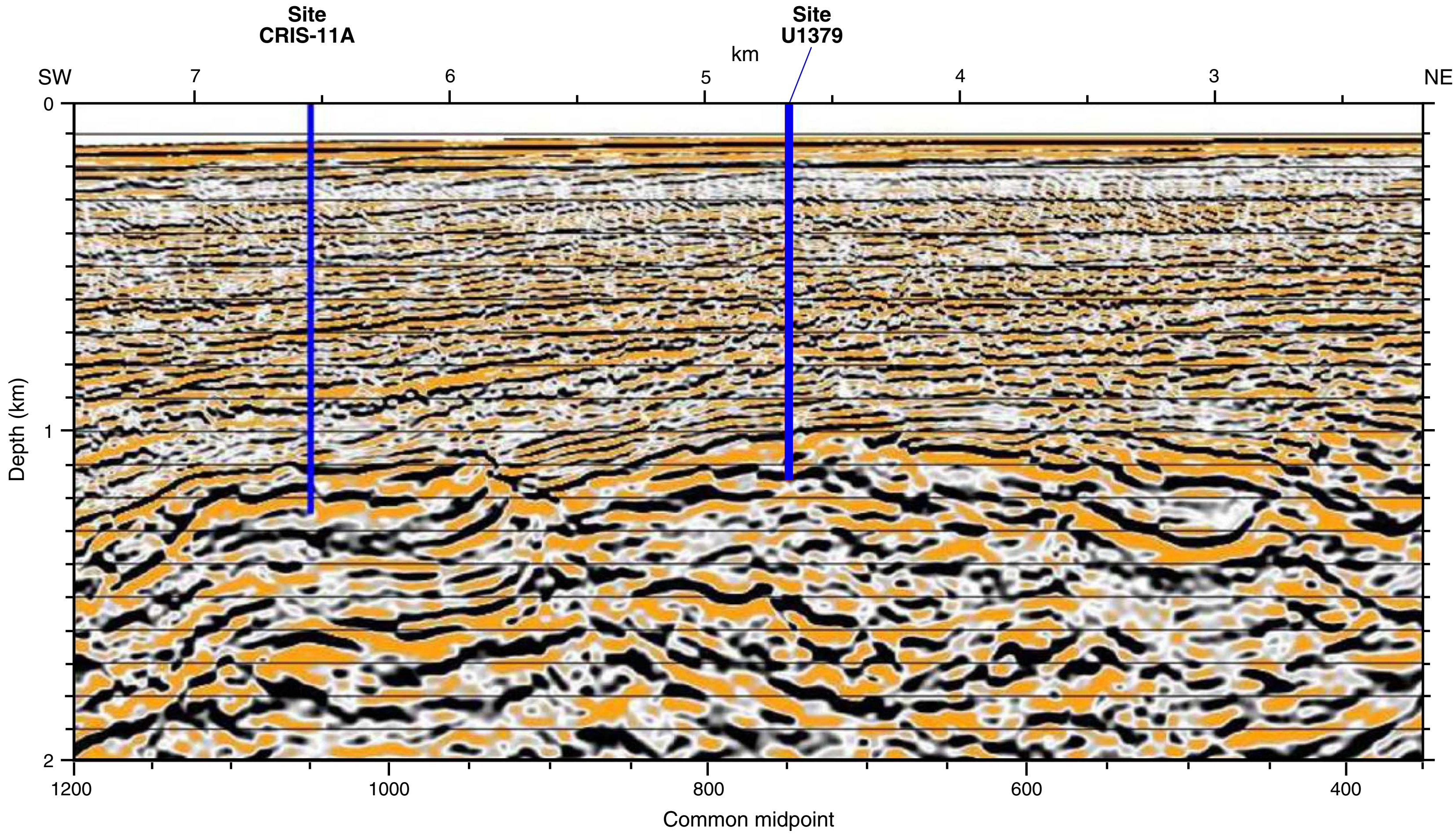


Figure AF8. Proposed alternate Site CRIS-14A (Inline 1090, XLine 2115).

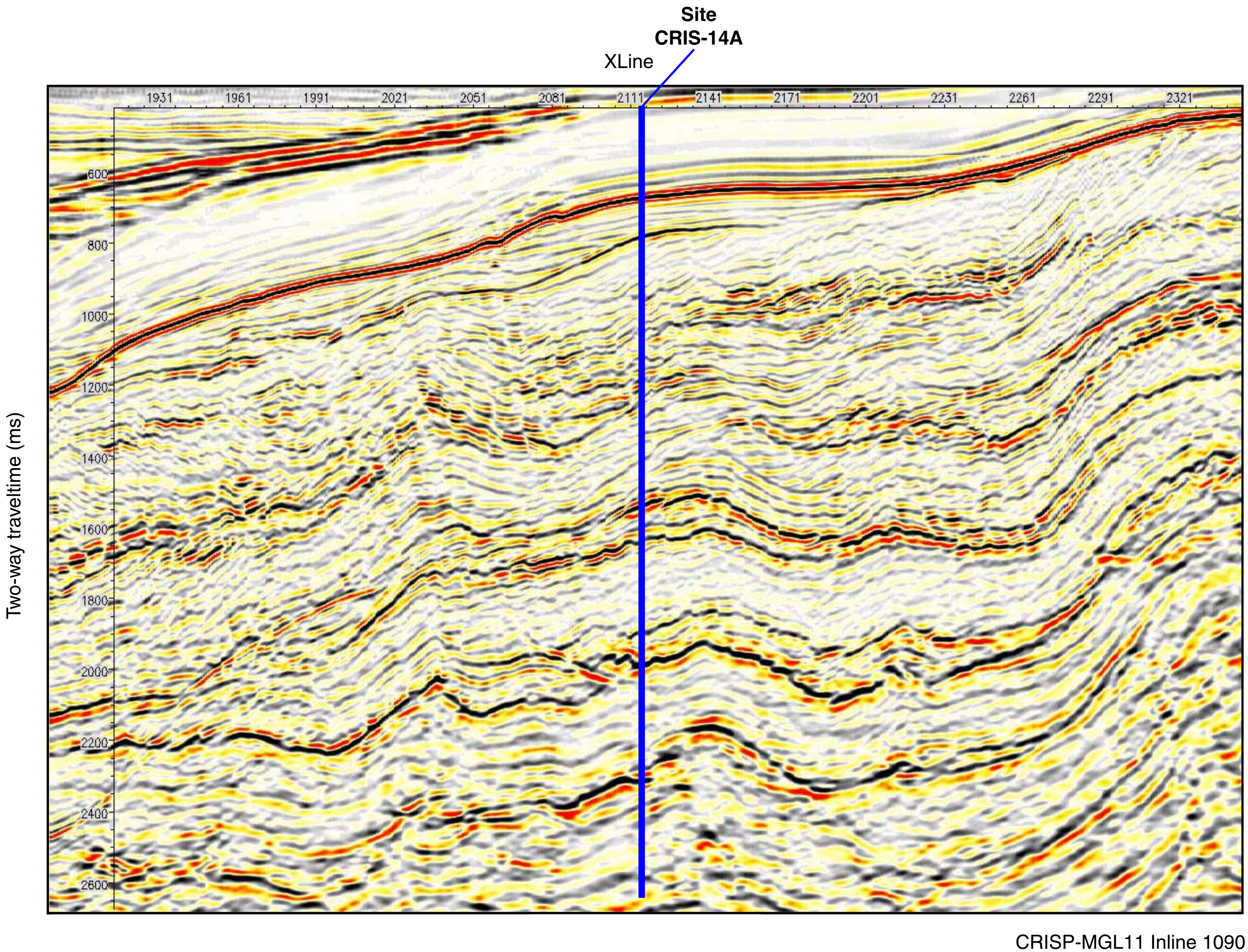


Figure AF9. Proposed alternate Site CRIS-15B (Inline 1160, XLine 2025).

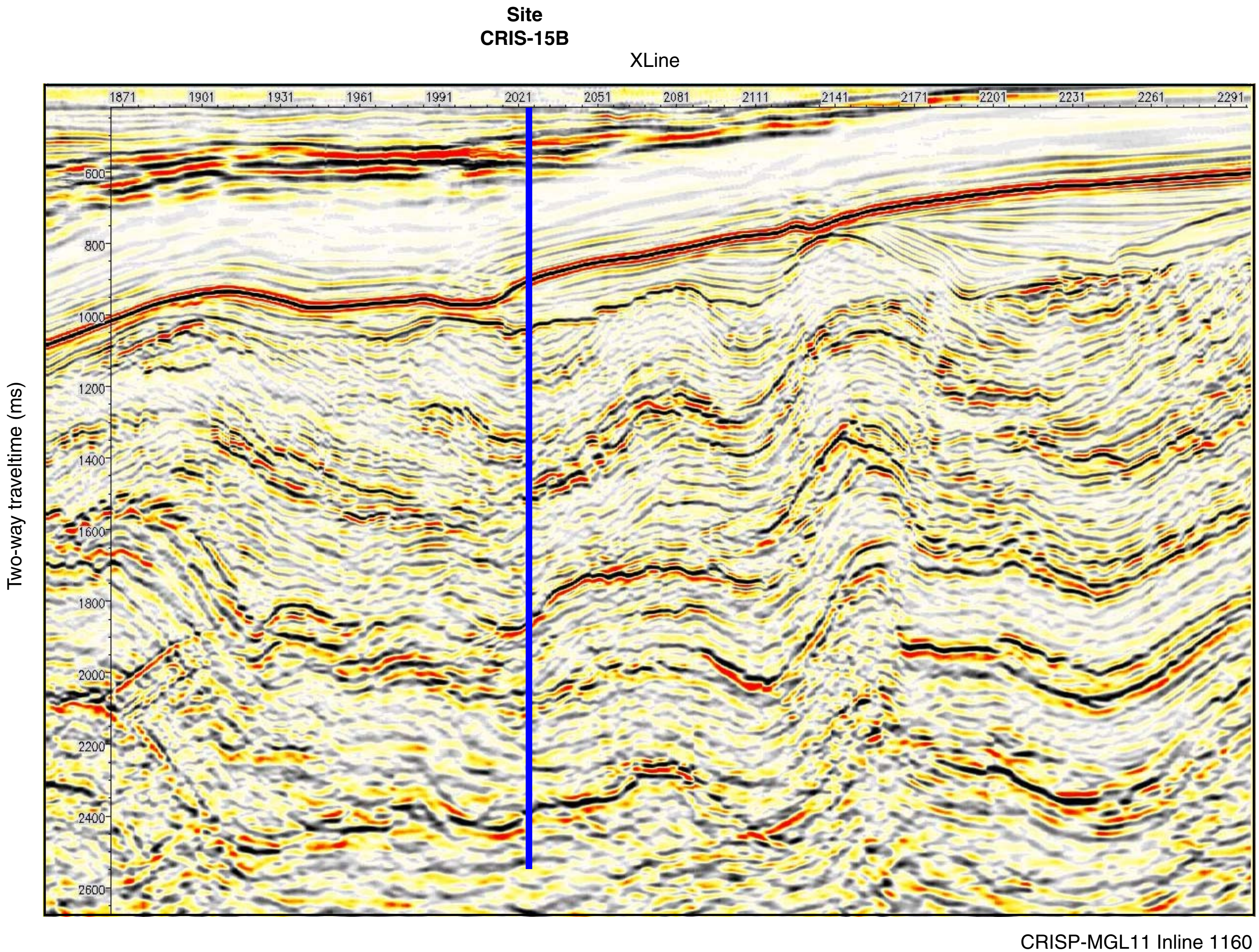
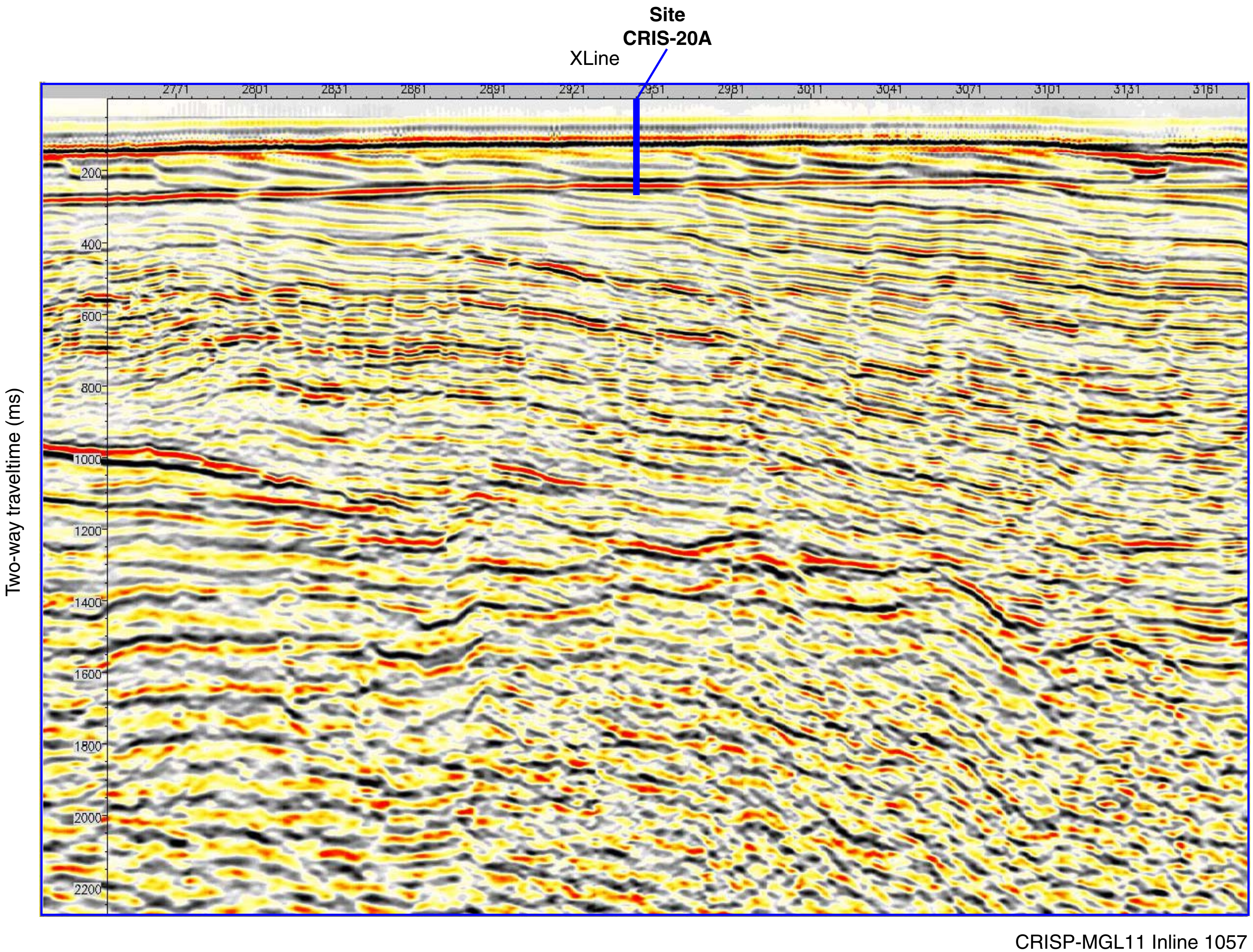


Figure AF10. Proposed contingency Site CRIS-20A (Inline 1057, XLine 2945).



Expedition scientists and scientific participants

The current list of participants for Expedition 344 can be found at **iodp.tamu.edu/scienceops/precruise/costarica/participants.html.**