Integrated Ocean Drilling Program Expedition 334 Scientific Prospectus

Costa Rica Seismogenesis Project (CRISP)

Sampling and quantifying input to the seismogenic zone and fluid output

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Abstract

The Costa Rica Seismogenesis Project (CRISP) is designed to understand the processes that control nucleation and seismic rupture of large earthquakes at erosional subduction zones. CRISP involves the only known erosional end-member of convergent margins 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 learn causes of 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 334 is based on a part of CRISP Program A (Integrated Ocean Drilling Program Proposal 537A-Full5), which is the first step toward the 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 might also serve as pilot holes for potential future proposed riser drilling to reach the aseismic/seismic plate boundary.

Schedule for Expedition 334

Expedition 334 is based on part of Integrated Ocean Drilling Program (IODP) drilling proposal number 537A-Full5 (available at **iodp.tamu.edu/scienceops/precruise/costarica/CRISP_summary.html**). Following ranking by the IODP Scientific Advisory Structure, the expedition was scheduled for the research vessel R/V *JOIDES Resolution,* operating under contract with the U.S. Implementing Organization (USIO). At the time of publication of this *Scientific Prospectus,* the expedition is scheduled to start in Puntarenas, Costa Rica, on 15 March 2011 and to end in Balboa, Panama, on 14 April 2011. A total of 25 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 key objective of the Costa Rica Seismogenesis Project (CRISP) is to understand the physical processes that generate earthquakes. This could be achieved through drilling the seismogenic zone and long-term near-source monitoring of this dynamic environment. During the past three decades, the tectonically active near-trench areas of convergent margins have been drilled several times. However, natural hazards relevant to society such as earthquakes, tsunamis, and volcanism occur in parts of the subduction system that are too deep to be directly sampled by conventional drilling technology. The improved capabilities of IODP allow exploration of the seismogenic zone, which is a primary scientific objective highlighted in the Initial Science Plan for IODP. The Central American margin offshore the Osa Peninsula of Costa Rica is a region where the processes that lead to the onset of seismicity can be addressed because of the abundant earthquake activity and because the seismogenic zone is within the operational capabilities of the IODP riserless drillship and the D/V *Chikyu* (riser drillship).

Expedition 334 is based on part of IODP Proposal 537A-Full5 (CRISP Program A). 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 sites (CRIS-3B and CRIS-4A; Fig. **F1, F2**) which will serve as pilot holes for future riser drilling (CRISP Program B). CRISP Program B aims to reach the plate boundary, observe physical conditions, and sample fault zone material before and after the onset of seismogenic behavior of large earthquakes.

Background

Subducting plate and the Cocos Ridge

The oceanic Cocos plate subducting beneath Costa Rica has been formed at two ridges: the East Pacific Rise (EPR) and the Cocos-Nazca Spreading Center (CNS), and it has been intruded by Galapagos hotspot volcanism. The Cocos Ridge (Fig. **F1**) was formed by the passage of the Cocos plate over the Galapagos hotspot. The ridge stands 2.5 km high and has crust of Galapagos-type geochemistry three times the normal oceanic thickness (i.e., 25 km) (Stavenhagen et al., 1998). Bordering the ridge to the northwest is regular CNS oceanic crust, 40% of which is covered by younger seamounts (Fig. **F1**) having Galapagos geochemistry. In this area, the seamounts impart a rough morphology to the Cocos plate. Further north, the EPR-generated crust has a smoother morphology. The area drilled during Deep Sea Drilling Project Leg 84 and Ocean Drilling Program (ODP) Legs 170 and 205 (Kimura, Silver, Blum, et al., 1997; Shipboard Scientific Party, 1985, 2003) lies just northwest of the EPR/CNS crustal boundary (Barckhausen et al., 2001). Sills with a Galapagos-type geochemistry drilled at ODP Sites 1039 and 1253 show the great lateral extent of hotspot magma intrusion.

The influence of Cocos Ridge subduction increases from the Nicoya Peninsula in the northwest to the Burica Peninsula to the southeast (~400 km; Fig. **F1**) and corresponds to the onset of morphologic changes along the margin in response to shallowing of the Wadati-Benioff Zone. The seismically active slab dips at ~65° near the Nicaraguan border and shallows a few degrees inboard of the Cocos Ridge. The timing of the Cocos Ridge impinging on the Middle America Trench is an unresolved issue, with estimates ranging from ~1 Ma (Hey, 1977; Lonsdale and Klitgord, 1978) to Miocene time (Sutter, 1985). 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 Terraba forearc basin directly inboard of the Cocos Ridge (Kolarsky et al., 1995) raise serious concerns about this model. A second question is when the Cocos Ridge first formed. Several investigators have proposed a date of ~20–22 Ma, synchronous with the formation of the CNS (Lonsdale and Klitgord, 1978; van Andel et al., 1971).

Upper plate and onland geology

On the landward side of the Middle America Trench offshore the Osa Peninsula, the lower slope consists of a 10–12 km wide frontal prism (Fig. **F3A**). The same feature, 3–5 km wide, is also present offshore the Nicoya Peninsula, where it is composed of slope sediment redeposited into the trench and buttressed against a forearc basement that, although poorly sampled during Leg 170, is generally accepted to be composed of the same igneous rock exposed onshore (Kimura, Silver, Blum, et al., 1997; Ye et al., 1996). The igneous complexes exposed in Costa Rica represent parts of the Caribbean Large Igneous Province (CLIP), emplaced between 74 and 94 Ma (Sinton et al., 1998), as well as accreted ocean islands and aseismic ridge terranes (Hauff et al., 1997, 2000; Sinton et al., 1997). Crucially, there is no evidence that the forearc comprises a complex of tectonized sediments offscraped from the currently subducting plate, although the 60–65 Ma Quepos and Osa terranes are interpreted to reflect rocks accreted from subducted edifices generated by the Galapagos hotspot (Hauff et al., 1997). Moving south from the area of operations for Legs 84, 170, and 205 and focusing on the CRISP transect, the forearc basement is interpreted to be composed of a middle Eocene–middle Miocene mélange of oceanic lithologies accreted to the overriding plate. The Osa Mélange, dominated by basalt, radiolarite, and limestone, is the most seaward unit found on land close to the CRISP transect. The nature and significance of the Osa Mélange is still under discussion, being variously interpreted as debris flows that were subsequently accreted to the margin (P.O. Baumgartner, pers. comm., 2002), as a tectonic mélange produced by subduction erosion (Meschede et al., 1999), or as 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 can expect to drill as upper plate basement during CRISP.

A major unknown is the nature of the high-amplitude landward-dipping reflectors cutting through the forearc basement (Fig. **F3A**). They branch upward from the plate interface similarly to “splay faults” (Park et al., 2002). Our interpretation, though, suggests that these surfaces represent old faults, related to a middle Eocene–middle Miocene accretionary event, now sealed by the slope apron sediment, and with only a few of them reactivated as normal faults. Only a few of them have offsets at the top of the forearc basement into the slope apron, and these indicate normal faulting, as commonly occur offshore the Nicoya Peninsula and Quepos (McIntosh et al., 1993; Ranero and von Huene, 2000). The lack of a clear thrust sequence, instead, argues against the presence of out-of-sequence thrusts (OOSTs) cutting the forearc. The presence of such discontinuities into the forearc basement can offer preexisting planes of weakness and play a role in focusing fluid flow drained from the deeper part of the margin as suggested by the high reflectivity and the high heat flux. However, the nature 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 its modern functioning.

Finally, the CRISP drilling area has experienced the subduction of the Cocos Ridge, which has caused (1) the extinction 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.

Volcanic arc

In Costa Rica, new $^{40}Ar/^{39}Ar$ 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 is a high-priority study area of the Subduction Factory initiative of the U.S. 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 shut down 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). The interpretation is based on

- 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 on the forearc and marking the slope apron–forearc basement unconformity, and proved that the margin offshore Nicoya Peninsula has experienced a net loss of crust since ~16 Ma (Vannucchi et al., 2001). Detailed analysis on 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 subsidence acceleration, probably linked to the arrival of the Cocos Ridge at the subduction zone (Vannucchi et al., 2003), is our best proxy for faster subduction erosion 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 up to 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.
- 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

Active fluid venting indicated by elevated methane concentrations in the bottom water have been observed along the entire Costa Rican margin (Bohrmann et al., 2002; Kahn et al., 1996; McAdoo et al., 1996). 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 (Bohrmann et al., 2002; Kahn et al., 1996; Ranero et al., 2008). Mud volcanoes and mud diapirs have also been found, particularly across the middle slope. They are associated with a high density of chemosynthetic vents, indicating that they may be effective in transporting fluids in the overpressured slope sediments (Bohrmann et al., 2002; Shipley et al., 1992; Weinrebe and Flüh, 2002). Drilling will help clarify fluid sources and pathways. Sampling during Leg 170 revealed freshened pore waters containing thermogenic methane, propane, and heavier hydrocarbons along the décollement, which, along with freshwater from dissociated gas hydrate, was dispersed into the upper plate sediment (Kastner et al., 1997; Silver et al., 2000). These fluids contrast with water from below the décollement that has near-seawater salinity

(Kimura, Silver, Blum, et al., 1997). Because downhole temperatures measured during Leg 170 are insufficient to support mineral dehydration and thermogenic methane, a lateral flow from depths of 15–20 km within the subduction system is implied (Kimura, Silver, Blum, et al., 1997). Offshore Nicoya Peninsula, measurements of diffuse fluid flow near the seafloor indicate complex circulation patterns attributed to the underlying structure of this margin (Tryon and Brown, 2000), although we recognize that much of the diffuse flow is likely from local, rather than deep, sources.

The importance of the hydrological activity in the subducting oceanic plate is just beginning to be appreciated (Silver et al., 2000), and because the Cocos Ridge upper crust is well layered and probably very porous (C.R. Ranero, pers. comm., 2003), the contribution from the lower plate to the fluid circulation could be significant in the drilling area.

Seismic reflection data

Seismic reflection images collected between Osa and the Cocos Ridge (Fig. **F3A**) show more stratified forearc basement and lower velocity material (~1 km/s less) than in equivalent areas along the Nicoya transect. Contact between the Osa Mélange and a separate forearc igneous basement is indicated in wide-angle seismic data, reflection data (Fig. **F3B**), and magnetic modeling.

Short-wavelength magnetic anomalies beneath the Osa continental shelf are interpreted as localized bodies of igneous rock mixed with sedimentary rocks (U. Barckhausen, unpubl. data). Dredged rock samples from the Cocos Ridge and related seamounts give ages of 13.0–14.5 Ma near the trench (Werner et al., 1999). This leaves a 45 m.y. gap in the geologic record between the Galapagos hotspot activity preserved in the Cocos Ridge and the CLIP (74–94 Ma). Rocks emplaced during this gap may be partially recorded in rock accreted beneath the Osa continental slope-forearc (Hoernle et al., 2002).

Heat flow

Two recent heat flow surveys (Ticoflux I and II) offshore Nicoya investigated in detail the thermal structure of the incoming plate seaward of the trench, whereas the R/V *METEOR* Cruise 54-2 concentrated on the upper plate from Nicaragua to southern Costa Rica. The heat flow values measured support the idea that the boundary between EPR- and CNS-generated crust is a major thermal boundary, not only seaward of the trench, but also below the upper plate (Kimura, Silver, Blum, et al., 1997; Langseth and Silver, 1996).

In the proposed drilling area offshore the Osa Peninsula, considerable thermal data can be inferred from 10 closely spaced seismic lines that show bottom-simulating reflectors (BSRs) and which are arranged along the drilling transect (Ranero et al., 2008). These BSR depths may be converted to temperature and compiled for analysis within a three-dimensional (3-D) model of the plate boundary using conductivity data from Leg 170 (Fig. **F4**). Uncertainties are introduced by the major thermal boundary between the Leg 170 area and the CRISP area, but nonetheless, estimated temperatures at the plate boundary beneath the proposed midslope site fall within the range 141°–200°C. Conductivity measurements to be made during Expedition 334 will allow improved temperature estimates at the plate boundary.

Seismogenic zone and earthquakes

CRISP Program A is preparatory to the seismogenic zone experiment and will define the tectonic reference for deeper drilling. A full overview of the seismogenesis studies offshore the Osa Peninsula is provided in the CRISP complex drilling project document. Here we want to stress that from teleseismic waveform modeling the main shock of the June 2002 Mw 6.4 underthrusting earthquake and its aftershock sequence (Fig. **F5**), which occurred just to the south of the August 1999 event, appears to occur at ~9 km depth (S.L. Bilek, pers. comm., 2003), shallower than the 1999 earthquake sequence. This may reflect along-strike variations in the updip extent of the seismogenic zone or its transitional nature.

Global Positioning System (GPS) measurements on land indicate high stress over the subducted Cocos Ridge with most of the plate interface in the seismogenic region essentially fully locked (Dixon, 2003). In contrast, seismic profiles indicate fault geometries (i.e., angles between forethrusts, backthrusts, and the décollement), suggesting 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 are able to accommodate seafloor relief at the front of the margin without much deformation. Fluids draining from the subducting lower plate are sufficient to hydrofracture and to mobilize about a 1–2 km thick and 20 km long section of the upper plate material every million years in Central America.

Site survey data

The supporting site survey data for Expedition 334 are archived at the **IODP Site Survey Data Bank.**

The regional framework of Central America Trench off Costa Rica is well known from investigations since Deep Sea Drilling Project 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, it has been the focus area 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 U.S. MARGINS National Science Foundation program (**www.nsf-margins.org/SEIZE/CR-N/CostaRica.html**). The results are more than 10,000 km of seismic data acquisition and extensive bathymetric imaging (swath bathymetry: Weinrebe and Ranero, in GeoMapApp and MARGINS Data Portal) (Fig. **F6**). The extensive multibeam bathymetric mapping started after the results from SO-76 of the German R/V *Sonne,* which showed a varying seafloor morphology from offshore the Nicoya Peninsula to offshore the Osa Peninsula (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 GEOMAR 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. Several marine seismological network 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 more than 9 months (i.e., from the beginning of October 2002 [*METEOR* cruise M54-3B] to August 2003 [*Sonne* cruise SO173-1]) (Flüh et al., 2004). SO 173-1 also deployed another 2 months of OBS offshore in 2002. They recorded the Mw 6.4 main shock and aftershock sequence northwest of the Osa Peninsula (I. Arroyo et al., unpubl. data). The latter sequence surrounds the drilling scheduled in 2011.

Geophysical data acquisition in the proposed Osa drilling area is extensive. Besides the already mentioned CRSEIZE transect (Newman et al., 2002; Norabuena et al., 2004), the proposed 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. **F3B**) 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**). During 1991 and 1992, the German research vessel *Sonne* made two cruises (SO-76 and SO-81) that greatly expanded swath mapping, seismic reflection, and refraction coverage from the area off the Nicoya Peninsula for ~250 km to the southeast where the crest of Cocos Ridge is subducted (Fig. **F1**). The interpretation of the seismic reflection data from SO-81 (Hinz et al., 1996) complement those acquired in 1999. Two of BGR99 records are processed in the depth (Fig. **F3A**) and the remainder in time domains. The principal site survey line is flanked on either side by 2 lines at 1 km spacing, then by lines at 2 km, 5 km, and 10 km spacing (Fig. **F2**). 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. Proposed sites have cross-lines of industry and academic heritage. Transducer and high-resolution sparker coverage is available. Conventional heat probe transects were acquired regionally and along the primary transect, which calibrate BSR-derived heat flow from the seismic records (Ranero et al., 2008; R. Harris et al., unpubl. data). 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).

Scientific objectives

Overall, the CRISP program is designed to understand seismogenesis along erosional margins. CRISP Program A is the first step toward deep riser drilling through the seismogenic zone. CRISP Program A 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, will be also a priority of CRISP Program A.

CRISP Program A involves drilling along a transect offshore the Osa Peninsula in Costa Rica. Proposed middle slope Site CRIS-3B (or alternate Site CRIS-10A) and upper slope Site CRIS-4A (or alternate Site CRIS-11A) are the primary proposed sites for this expedition (Fig. **F3A**). These two sites are also proposed to be eventually deepened to reach the aseismic/seismic plate boundary. In our contingency plan, we include two additional sites (Fig. **F3A**): proposed base of the slope Site CRIS-2B (or alternate Site CRIS-9A) and incoming plate Site CRIS-1A (or alternate Site CRIS-7A), to consider in the event we are unable to perform operations as planned at the primary sites (see **"Risks and contingency"**).

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 the input into the erosive plate boundary. The plate boundary migrates upward and upper plate material is dragged into the subduction channel, which comprises 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 is needed to 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. From what is exposed on land, the Osa Mélange is the result of 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. Indications on the thickness of the subduction channel is critical for preparatory structural geology work and the concept of describing the active slip surface and the damage zone for CRISP Program B. To estimate the thickness of the subduction channel, namely the zone of broken upper-plate material currently subducting, we need quantification of mass removal in the CRISP study area. A two-point recovery of fossiliferous sediment across the margin would 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. Along the CRISP transect we expect the process to be accelerated.

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 stand-alone project providing data to solve longstanding problems related to tectonics of the region. These primary objectives are

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 shut off 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.

Objectives of the contingency plan (Sites CRIS-2B and CRIS-1A)

Proposed Site CRIS-2B is located at the frontal sedimentary prism representing the base of the slope. This site provides sampling of the plate boundary at a shallow depth through the sedimentary frontal prism to define fault state, composition, and fluid system. Proposed Site CRIS-2B will be drilled through a 320 m thick sedimentary pile, penetrating the plate boundary, and continue for 280 m into the underthrust sediment and 150 m into the oceanic basement. Drilling at proposed Site CRIS-2B will allow us to constrain the décollement geometry and deformation at a shallow depth, define fluid pathways, and link it to the seismic cycle.

Proposed Site CRIS-1A represents an oceanic reference site on the Cocos plate. Drilling at this site will define the sedimentary and upper part of the igneous section entering the subduction zone and the hydrologic system. Proposed Site CRIS-1A will penetrate ~150 m into the oceanic basement, allowing description of the igneous mineralogy, petrology, geochemistry, and hydrological input to the subduction zone. Fluids from the Cocos Ridge oceanic basement are expected to reveal low to moderate temperature alteration from near-trench fluid flow along ridge-parallel faults. Faults expose the oceanic basement and could be fluid pathways for recharge and discharge of seawater.

Drilling and coring strategy

Drilling strategy

The overall operations plan and time estimates are summarized in Table T1. An alternate operations plan substituting logging while drilling (LWD) for wireline logging has been prepared and is summarized in Table T2. Alternate sites have been selected and are presented in Table T3. 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). After departing from Balboa, Panama, we will transit for ~1.6 days to the Costa Rica sites and prepare for drilling operations.

The proposed drilling strategy is to begin by drilling at proposed Site CRIS-3B following by proposed Site CRIS-4A. Two holes will be cored at the each site. At both sites, the first hole will be cored with the advanced piston coring (APC) system to refusal. The coring system will then be changed over to the extended core barrel (XCB) system and will be cored to refusal, which has been estimated at 500 meters below seafloor (mbsf). The second hole will be drilled to just above the final depth of Hole A and will then be cored with the rotary core barrel (RCB) coring system to ~950–1000 mbsf. Temperature and pressure measurements will be taken at both sites in order to try to establish temperature and pressure gradients for both sites (see **"Downhole tools and logging strategy"**).

As per policy, all holes in continental margins into consolidated sediments will be plugged and abandoned with cement plugs.

Drilling operations in shallow water require special operational precautions to ensure safety for crew and equipment. Weather conditions (particularly sea state and resulting heave behavior of the vessel) are critical (see **"Risks and contingency"**).

Coring strategy

The first hole at each site (Hole A) will be cored with APC/XCB to refusal depth (estimated to be ~500 mbsf). The second hole (Hole B) at each site 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. While drilling/coring, a number of advanced piston coring temperature tool (APCT-3) and sediment temperature (SET)/sediment temperature pressure (SET-P) probe measurements will be made, as formation conditions permit, to complement existing data. Core orientation with the FlexIt tool will also be measured during the APC-cored sections at each site.

After completing coring in Holes A and B at each site, the hole will be conditioned, displaced with logging mud, and the hole will be logged as per the logging plan (see **"Downhole tools and logging strategy"**).

Downhole tools and logging strategy

Downhole logs will be acquired at the CRISP sites to measure in situ physical properties, estimate compaction, and evaluate permeable horizons. Electrical resistivity images referred to magnetic north will be used to determine fracture orientations, to infer stress directions from borehole breakouts, and to orient core samples. Formation density and velocity measurements will allow for constructing synthetic seismograms to correlate depth in the hole with traveltime in seismic sections. In situ velocity data will also be used to build a velocity model for a 3-D seismic survey planned for the Expedition 334 study area.

Logging operations will include one or more of the following: wireline logging, LWD, and logging while coring (LWC). Wireline logging is expected to be challenging at the CRISP sites because the deep holes are likely to be unstable after coring. LWD is expected to acquire better data in this environment, and it was successful in previous expeditions at convergent margins (e.g., Leg 170 and IODP Expeditions 311 and 314). LWC is a less expensive alternative that does not acquire as many measurements as LWD; however, LWC takes core samples that are precisely located with respect to the logging measurements. The development of LWC is also an important engineering advance for IODP. At the time of the writing of this prospectus, funds to support LWD and/or LWC were not available. The default operations plan (Table **T1**) is for wireline logging, with an alternative plan for LWD (Table **T2**). The operations plan for LWC would be similar to that for LWD. A decision on whether funding is available to log the CRISP sites by LWD and/or LWC is expected by the third quarter of 2010.

Wireline logging

Three wireline tool strings are planned for the CRISP sites (Fig. **F7**). The first tool string to be deployed in each hole is the triple combination (triple combo) tool string, which measures hole diameter, natural gamma ray, bulk density, neutron porosity, and electrical resistivity. 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) tool 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, LWD, and LWC tools and operational constraints can be found at **iodp.ldeo.columbia.edu/TOOLS_LABS/index.html**

The operational time estimates for the wireline log deployments are in Table **T1.** The CRISP operations plan calls for drilling two holes at each site: Hole A to ~500 mbsf (cored by APC/XCB) and Hole B to total depth (cored by RCB). The triple combo and FMS-sonic tool strings will be deployed to log the shallow interval in Hole A and the deeper interval in Hole B. To maximize the chances of successful wireline logging, 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 Hole B of proposed Site CRIS-4A. If borehole conditions are favorable and time is available, a check shot may also be performed at proposed Site CRIS-3B.

Logging while drilling

The LWD bottom-hole assembly presently planned for the CRISP sites consists of two Schlumberger tools. From bottom to top, these are the EcoScope (measuring resistivity, neutron porosity, images of bulk density, natural gamma ray, and borehole diameter, and annular pressure while drilling [APWD]) and the TeleScope (measurement-while-drilling [MWD] telemetry and power). This tool combination provides a basic set of in situ physical property measurements and real-time pressure in the borehole, needed for gas monitoring (see below). If funding is available, additional LWD tool strings to be added are, in order of priority, the geoVISION (resistivity images for fracture and breakout interpretation), sonicVISION (*P*- and *S*-wave velocity), and seismicVISION (check shot data acquired while drilling).

LWD measurements will be made in a dedicated Hole A drilled first at each site. The advantage of this strategy is that detailed physical property logs will be available to optimize coring in subsequent holes. The LWD operations plan in Table T2 takes ~3 days/hole. This time will allow for logging the whole sediment section at expected rates of penetration (ROPs) of ~20 m/h. These are “gross” ROPs that include time for pipe connections. The allotted time is enough to reach the total depth objective in each hole if ROPs in the basement interval can be maintained at ~10 m/h. If ROPs in the basement are significantly slower, we will log as much as possible of the basement interval given the time constraint of ~3 days/LWD hole.

Because the first hole at each site will not be cored, we will need to monitor for gas with the LWD measurements. The key measurement to be carefully monitored is the APWD, transmitted in real time by the MWD tool. The possible occurrence of gas should be indicated by a sharp pressure decrease, which could be preceded by a pressure increase. If the final plan for CRISP includes LWD, a detailed protocol for gas monitoring will be developed following the protocol that was applied in Expedition 311. The protocol required preventive actions for any pressure anomaly exceeding 100 psi; no significant anomalies were detected in the Expedition 311 holes.

Logging while coring

An LWC system that combines a modified geoVISION resistivity LWD tool and a core barrel was tested during ODP Legs 204 and 209 (Goldberg et al., 2006). The geoVISION resistivity tool measures resistivity images and natural gamma ray, and the core barrel retrieves a 2.5 inch diameter core. The LWC system recovered up to 68% in sediment, whereas recovery was poor in hard rock because of a mismatched core catcher. The core catcher has since been modified, and better recovery is expected in hard rock.

LWC will be carried out in a dedicated hole drilled last at each site. The plan is to log the entire interval while taking cores in intervals selected to test the LWC system and to supplement core recovery in the previously drilled holes. The operations plan will be similar to that for LWD (Table T2) and take ~3 days/hole.

Temperature, pressure, and core orientation measurements

The scientific objective of the temperature measurement plan is to provide sufficient 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 APCT-3 in the interval where cores will be taken by APC and the SET 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. Finally, APC cores will be taken with a nonmagnetic core barrel and oriented with the FlexIt tool for paleomagnetic studies. The nonmagnetic core barrels will be used until overpull limits are exceeded.

Risks and contingency

Three principal factors could affect the implementation of the drilling plan:

1. Adverse hole conditions at the principal sites (e.g., encountering thick intervals of loose sediment/rock that can collapse into the hole).

2. Weather conditions that can limit the ability to drill in shallow water by exceeding the water depth–dependent restrictions on allowable heave.
3. Shallow hazards.

Hole conditions

Poor hole conditions at either site will be dealt with in the first instance by using frequent high-viscosity mud sweeps and or heavy mud to condition the holes. One possible remedial action if hole conditions prove to be problematic would be to case off the upper sections of a hole with a limited amount of casing (up to 600 m) which might be available if it is not used during one of the previous expeditions. However, casing, which also requires the installation of a reentry cone, will be employed only as a last resort because it will involve a significant time penalty that would almost certainly lead to the loss of one site from the planned drilling program. The advantages and disadvantages of casing use will have to be evaluated at sea should the need arise.

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. Station keeping turned out not to be a significant problem when shelf drilling was conducted on the New Jersey margin (ODP Leg 174A) and on Canterbury (IODP Expedition 317). However, 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.

Alternate sites

Seismic profiles of all proposed alternate sites (as well as all primary sites discussed above) are included in the **"Site summaries."**

Slope sites (CRIS-10A and CRIS-11A)

These sites serve as alternate sites for primary Sites CRIS-3B and CRIS-4A. If poor hole conditions or other operation difficulties encountered, we may move from primary sites to alternate sites if it is judged that better conditions may be encountered at such alternate sites.

Base of the slope site (CRIS-2B) and incoming plate site (CRIS-1A)

These two sites could be drilled as contingency sites if drilling at the two slope sites becomes impossible because of hole conditions or sufficient time remaining available. The base of the slope site (CRIS-2B) is the highest priority contingency site. The alternate for Site CRIS-2B is Site CRIS-9A, and the alternate for Site CRIS-1A is Site CRIS-7A.

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 co-chief scientists, staff scientist, and IODP curator on shore and curatorial representative on board ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postcruise sampling.

Shipboard scientists are expected to submit sample requests (at **smcs.iodp.org/**) 3 months before the beginning of the expedition. Based on sample 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 cruise 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, as well as, potentially, microbiological experiments. The upper plate basement we expect 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 some critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. These intervals may require special handling, a higher sampling density, reduced sample size, or continuous core sampling by a single investigator. A sampling plan coordinated by the SAC may be required before critical intervals are sampled.

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Table T1. Operations plan and time estimates, Expedition 334. (See table notes.)

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	Wireline Log (days)
Puntarenas, Costa Rica			**Begin Expedition** 2.0	port call days		
			Transit ~94 nmi to **CRIS-3B** @ 10.5	0.4		
CRIS-3B	8.5924° 0' N	549	Hole A - APC/XCB - 500mbsf and log with Triple Combo and FMS Sonic		3.2	0.7
EPSP	84.0772° 0' W		Hole B - Drill ahead to ~490mbsf and RCB core to 950mbsf then log		8.8	0.9
to 1000 mbsf			APCT3 and SET Temperature Measurements on Hole A			
			Sub-Total Days On-Site: 13.7			
			Transit ~6 nmi to **CRIS-4A** @ 6	0.1		
CRIS-4A	8.6808° 0' N	181	Hole A - APC/XCB to ~500mbsf and log with Triple Combo and FMS Sonic		2.6	0.8
EPSP	84.0336° 0' W		Hole B - Drill ahead to ~490mbsf and RCB core to 1000mbsf then log		7.8	1.2
to 1050 mbsf			APCT3 and SET Temperature Measurements on Hole A			
			Sub-Total Days On-Site: 12.4			
			Transit ~223 nmi to **Waypoint 1** @ 10.5	0.9		
			Transit ~170 nmi to **Balboa, Panama** @ 10.5	0.7		
Balboa, Panama			**End Expedition**	**2.1**	**22.4**	**3.6**

Port Call:	**2.0**	**Total Operating Days:**	**28.0**
Sub-Total On-Site:	**25.9**	**Total Expedition:**	**30.0**

Notes: Alternate site for CRIS-3B is CRIS-10A and alternate site for CRIS-4A is CRIS-11A. Shallow water guidelines to be used for both primary sites.

Table T2. Alternate operations plan with logging-while-drilling (LWD) option, Expedition 334. (See table notes.)

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	LWD/MWD Log (days)
Puntarenas, Costa Rica			**Begin Expedition** 2.0	port call days		
			Transit ~91 nmi to **CRIS-4A** @ 10.5	0.4		
CRIS-4A	8.6808° 0' N	181	Hole A - LWD to 950 mbsf			2.9
EPSP	84.0336° 0' W					
to 1050 mbsf						
			Sub-Total Days On-Site: 2.9			
			Transit ~6 nmi to **CRIS-3B** @ 6.0	0.1		
CRIS-3B	8.5924° 0' N	549	Hole A - LWD to 950 mbsf			3.0
EPSP	84.0772° 0' W		Hole B - APC/XCB to ~500mbsf		3.0	
to 1000 mbsf			Hole C - Drill to 490 mbsf and RCB to 950 mbsf		8.0	
			APCT3 and SET Temperature Measurements on Hole B			
			Sub-Total Days On-Site: 14.0			
			Transit ~6 nmi to **CRIS-4A** @ 6.0	0.1		
CRIS-4A	8.6808° 0' N	181	Hole B - APC/XCB to ~500mbsf		2.6	
EPSP	84.0336° 0' W		Hole C - Drill to 490 mbsf and RCB to 1000 mbsf		6.3	
to 1050 mbsf			APCT3 and SET Temperature Measurements on Hole B			
			Sub-Total Days On-Site: 9.0			
			Transit ~223 nmi to **Waypoint 1** @ 10.5	0.9		
			Transit ~170 nmi to **Balboa, Panama** @ 10.5	0.7		
Balboa, Panama			**End Expedition**	**2.2**	**19.9**	**5.9**

Port Call:	**2.0**	**Total Operating Days:**	**28.0**
Sub-Total On-Site:	**25.8**	**Total Expedition:**	**30.0**

Notes: Alternate site for CRIS-3B is CRIS-10A and alternate site for CRIS-4A is CRIS-11A. Shallow water guidelines to be used for both primary sites.

Table T3. Alternate sites for primary Sites CRIS-3B and CRIS-4A, Expedition 334. (**See table notes.**)

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbrf)	Operations Description	Drilling Coring (days)	Wireline Log (days)
CRIS-10A	8.6° 0' N	511	Hole A - APC/XCB - 500mbsf and log with Triple Combo and FMS Sonic	3.2	0.7
EPSP	84.0734° 0' W		Hole B - Drill ahead to ~490mbsf and RCB core to 800mbsf then log with	7.4	0.9
approved			Triple Combo and FMS Sonic		
to 800 mbsf					
			Sub-Total Days On-Site: 12.2		
CRIS-11A	8.6657° 0' N	211	Hole A - APC/XCB to ~500mbsf and log with Triple Combo and FMS Sonic	2.6	0.8
EPSP	84.0411° 0' W		Hole B - Drill ahead to ~490mbsf and RCB core to 1120mbsf then log with	8.4	0.9
approved			Triple Combo, FMS Sonic and VSI.		
to 1120 mbsf					
			Sub-Total Days On-Site: 12.7		

Notes: Alternate site for CRIS-3B is CRIS-10A and alternate site for CRIS-4A is CRIS-11A. Shallow water guidelines to be used for both primary sites.

Figure F1. Bathymetric map of Middle America Trench, showing location of proposed drilling area. Note the collision of Cocos Ridge with trench in Osa Peninsula area, a process that brings the seismogenic zone within reach of IODP riser drilling capabilities. Elevation data compiled from Smith and Sandwell. DSDP = Deep Sea Drilling Project, ODP = Ocean Drilling Program.

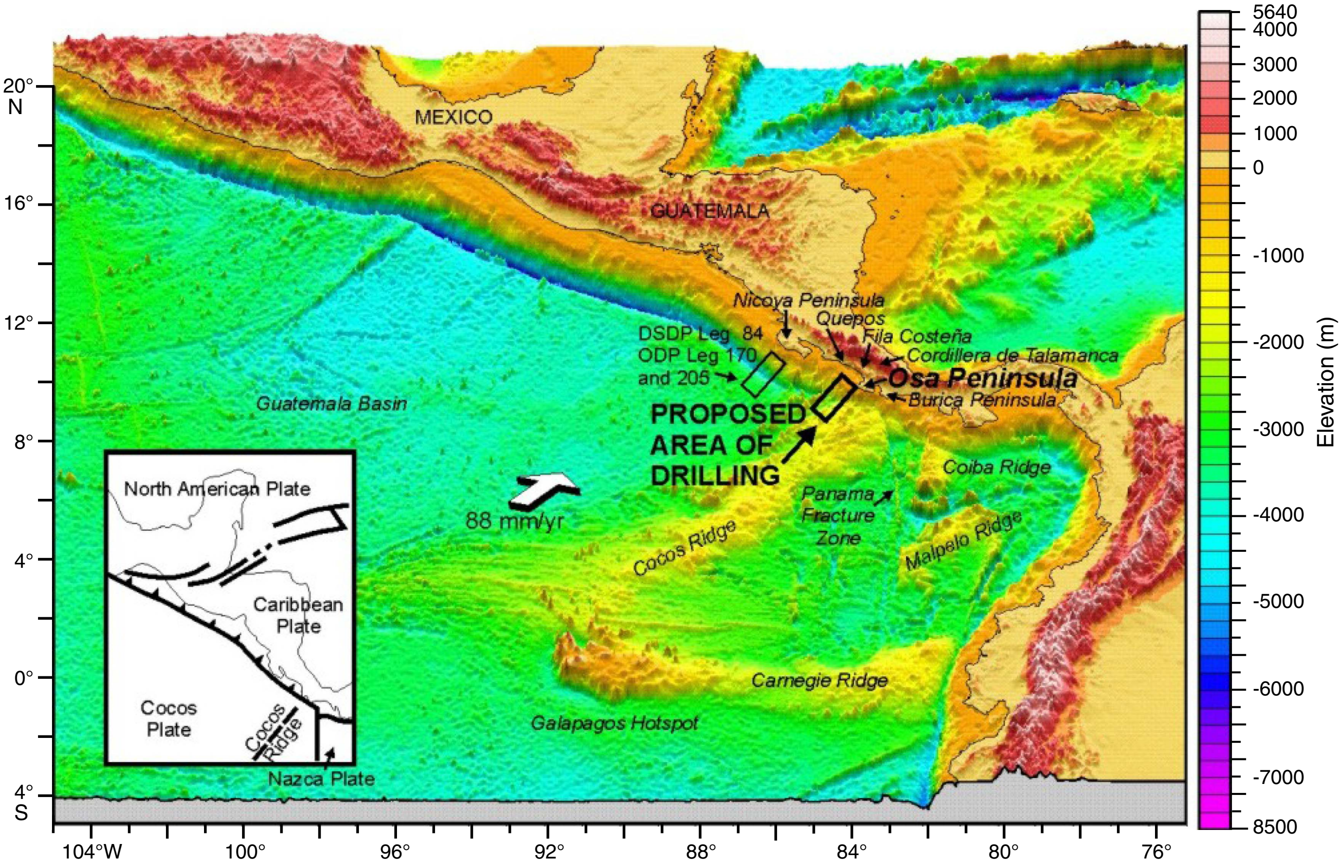


Figure F2. Location of proposed drill sites. Green squares = primary sites (CRIS-3B and CRIS-4A) and contingency sites (CRIS-2B and CRIS-1A), yellow squares = alternate sites for primary and contingency sites, red lines = seismic reflection BGR99 profiles.

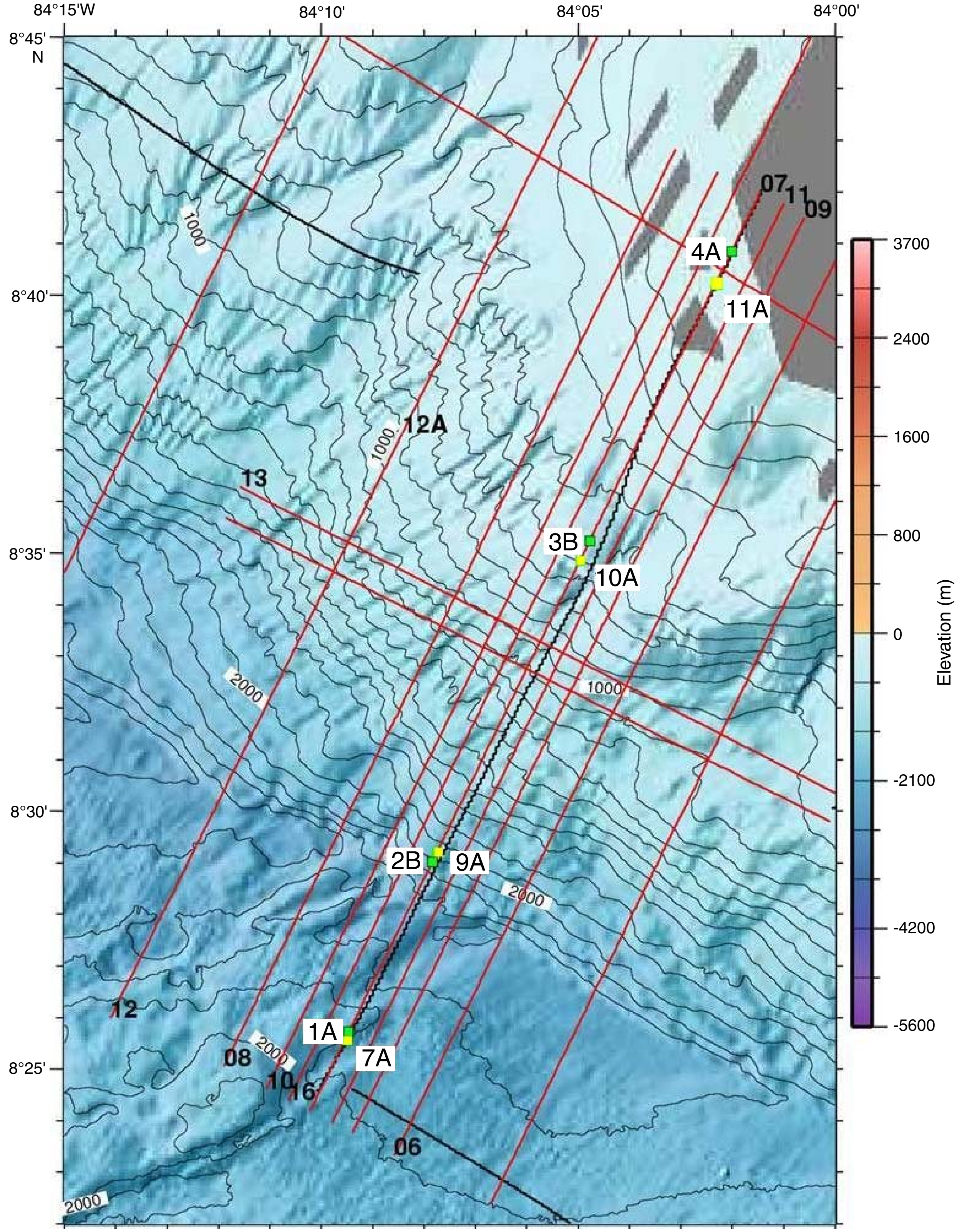


Figure F3. A. Seismic Line BGR99-7 showing location of proposed drill sites across Costa Rica margin offshore Osa Peninsula. Prestack depth migration (C.R. Ranero, unpubl. data) is at a vertical exaggeration of 1.3× (vertical axis is depth). (**Continued on next page.**)

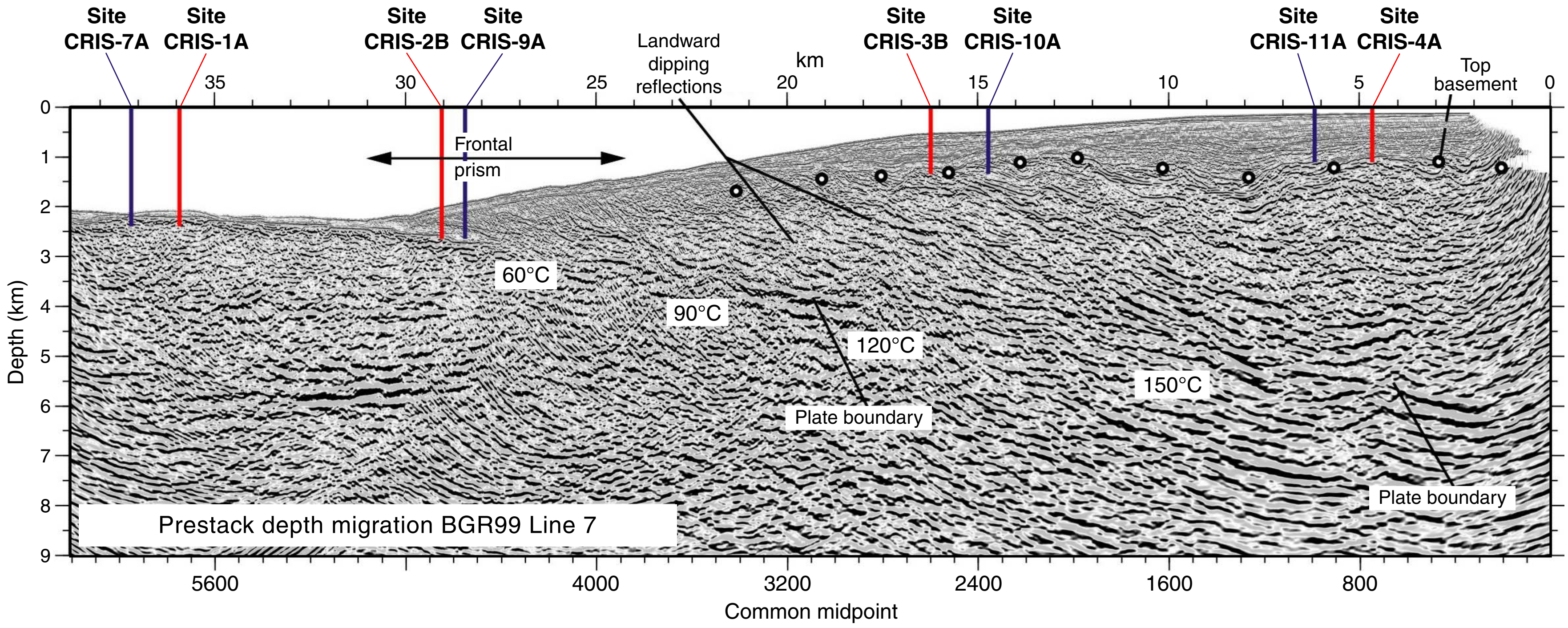


Figure F3 (continued). B. Interpreted wide-angle seismic section from Stavenhagen et al. (1998). Schematic figure through Osa Peninsula margin shows how proposed CRISP drill sites will sample different parts of the margin structure. CRISP Program A will focus on CRIS 3 and CRIS 4. VE = vertical exaggeration.

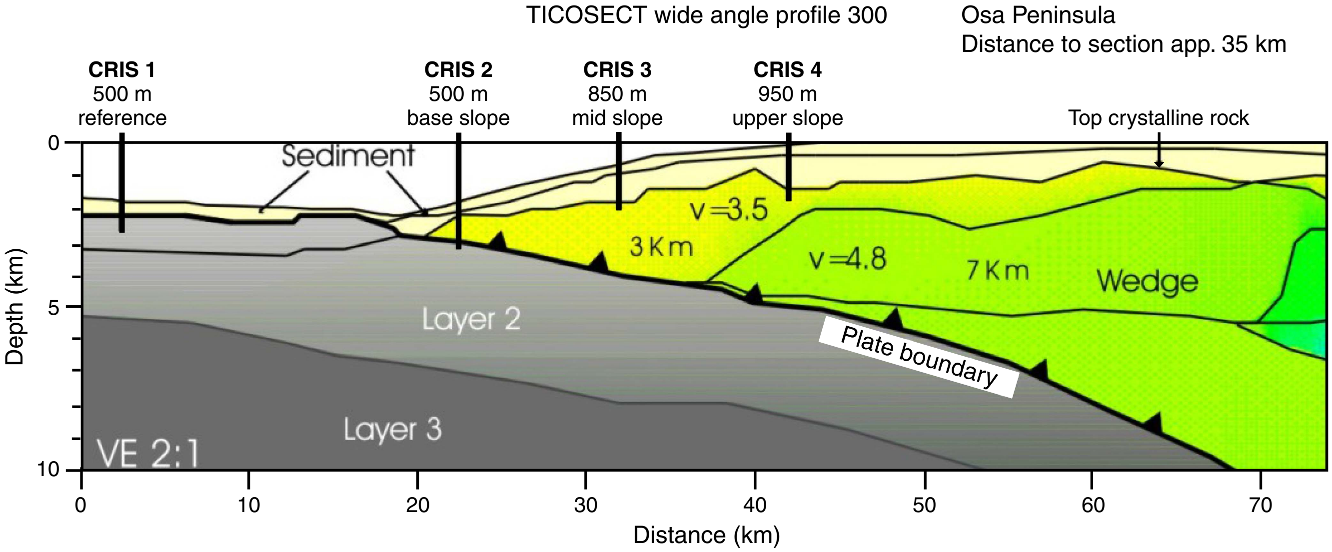


Figure F4. Multibeam bathymetry projected along the strike of trench offshore Nicoya Peninsula (0 km in projection). Sudden change in trench strike toward Osa Peninsula is interpreted as rapid margin retreat because of accelerated subduction erosion by Cocos Ridge and flanking seamounts. Temperature at plate boundary is shown as isotherms of 60°, 90°, 120°, and 150°C calculated from heat flow probes and depth to the BSR. Red circles = venting sites, where deeply sourced fluids, chemosynthetic carbonates, and fauna have been observed; black circles = earthquakes from Newman et al. (2002), Husen et al. (2003), and DeShon et al. (2003). CRISP = Costa Rica Seismogenesis Project.

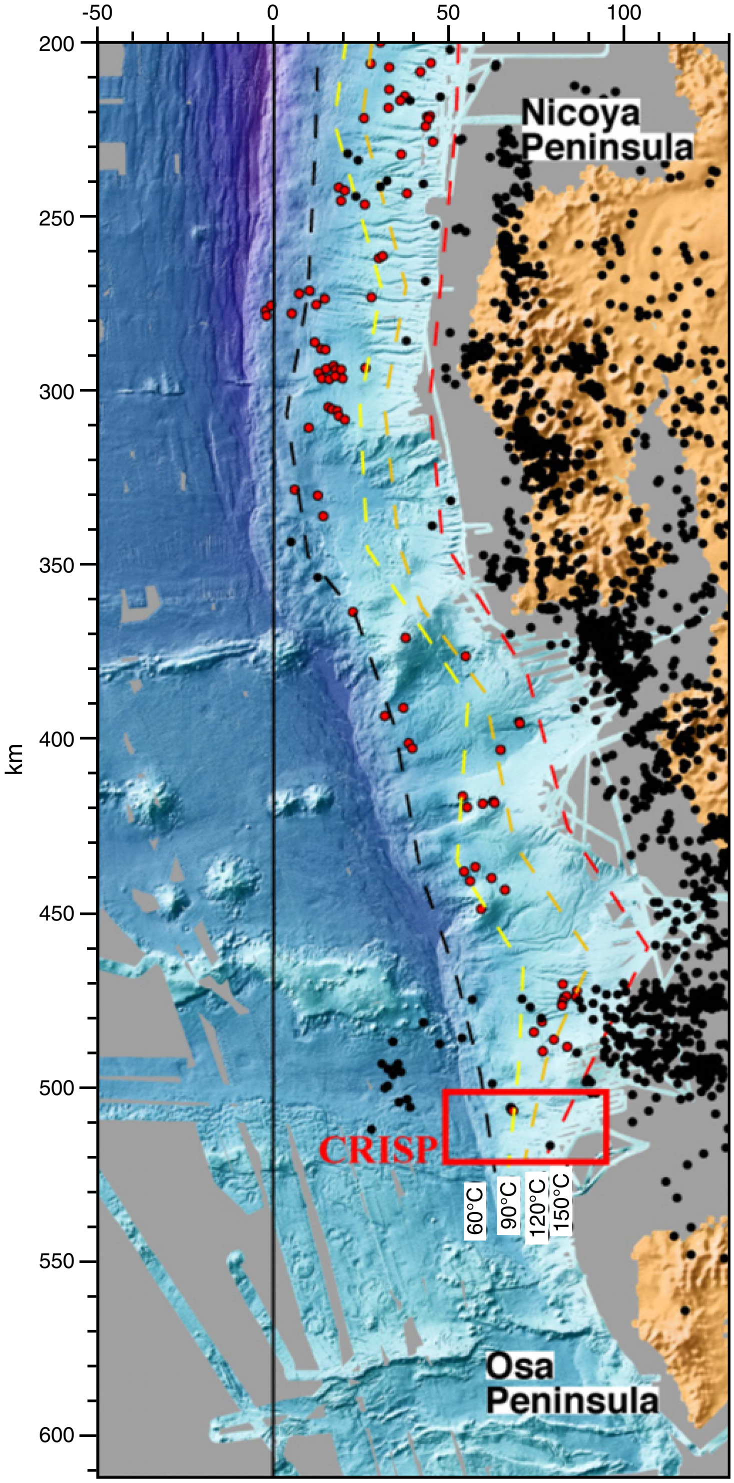


Figure F5. 2002 earthquake epicenter and aftershock sequence. Main shock was relocated by I. Arroyo (unpubl. data).

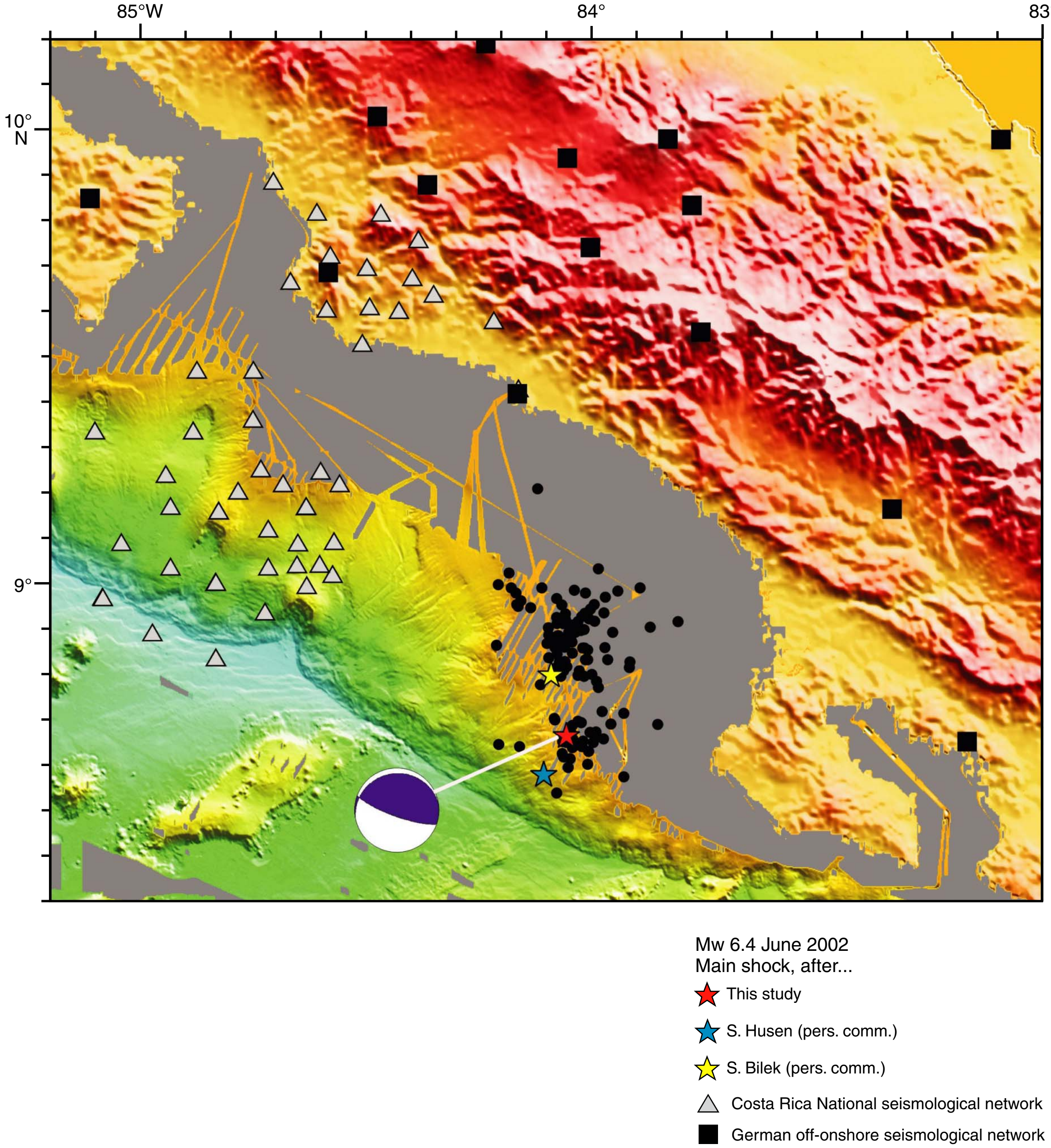


Figure F6. Central America Focus Site activity map (2008) (**media.marine-geo.org/image/central-america-focus-site-activity-map-2008-0**). SEIZE = Seismogenic Zone Experiment, OBS = ocean-bottom seismometers, TUCAN = Tomography Under Costa Rica and Nicaragua, ODP = Ocean Drilling Program, CORKS = circulation obviation retrofit kits, GPS = Global Positioning System, 3D = three-dimensional, IODP = Integrated Ocean Drilling Program, MCS = multichannel seismic, CRISP = Costa Rica Seismogenesis Project.

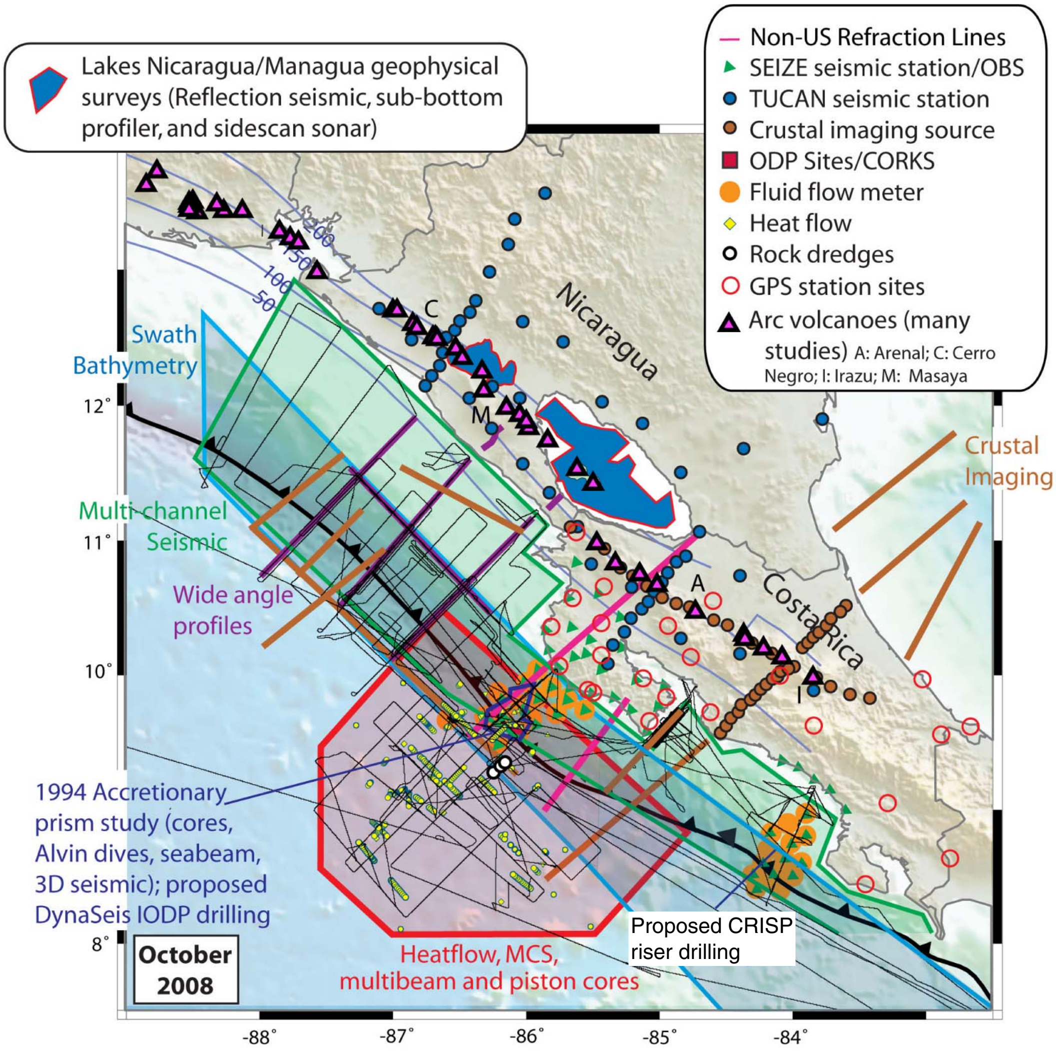
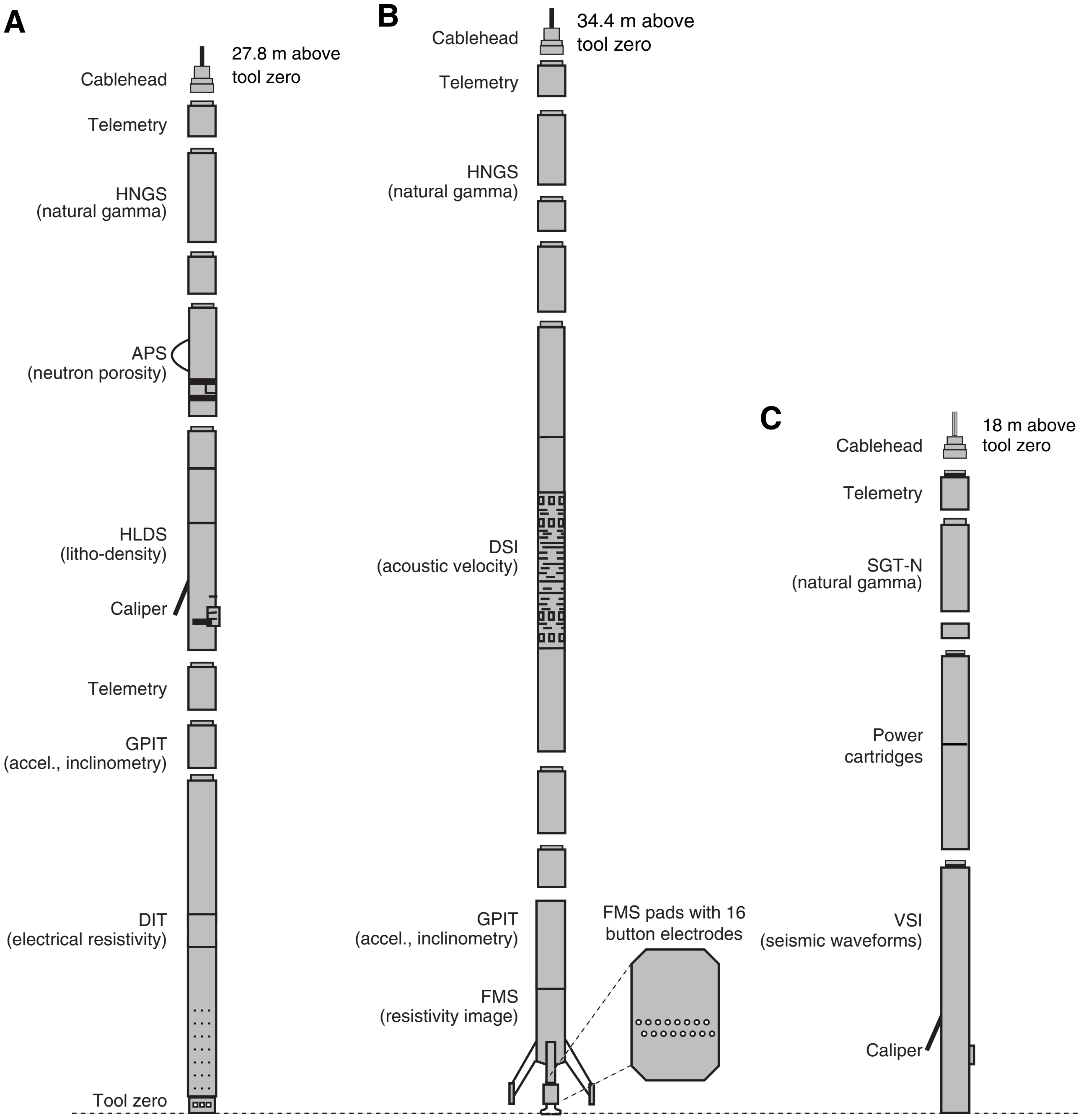


Figure F7. Wireline tool strings to be deployed at CRISP sites. **A.** Triple combo tool string takes downhole measurements of hole diameter, natural gamma ray, density, neutron porosity, and resistivity. **B.** Formation MicroScanner (FMS)-sonic tool string measures borehole resistivity images, natural gamma ray, and *P*- and *S*-wave velocities. **C.** Versatile Seismic Imager (VSI) tool string acquires seismic waveform data in a check shot experiment. HNGS = Hostile Environment Natural Gamma Ray Sonde, APS = Accelerator Porosity Sonde, HLDS = Hostile Environment Litho-Density Sonde, GPIT = General Purpose Inclinometry Tool, DIT = Dual Induction Tool, DSI = Dipole Sonic Imager, SGT-N = Scintillation Gamma Ray Tool-N.



Site summaries

Proposed Site CRIS-3B

Priority:	Primary
Position:	8.592356°N, 84.077177°W
Water depth (m):	538
Target drilling depth (mbsf):	950
Approved maximum penetration (mbsf):	1000
Survey coverage:	BGR 99-7 common midpoint (CMP) 2500 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF2**) • Location map (Fig. **F2**)
Objective:	Characterize upper plate basement and fluid flow.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 950 mbsf. • Conduct wireline logging or LWD/LWC and 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-4A

Priority:	Primary
Position:	8.680827°N, 84.033615°W
Water depth (m):	170
Target drilling depth (mbsf):	1000
Approved maximum penetration (mbsf):	1050
Survey coverage:	BGR 99-7 CMP 750 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF3**) • Location map (Fig. **F2**)
Objective:	Characterize upper plate basement and fluid flow.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 1000 mbsf. • Conduct wireline logging or LWD/LWC and 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-10A

Priority:	Alternate
Position:	8.599967°N, 84.073395°W
Water depth (m):	500
Target drilling depth (mbsf):	800
Approved maximum penetration (mbsf):	800
Survey coverage:	BGR 99-7 CMP 2350 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF2**) • Location map (Fig. **F2**)
Objective:	Alternate for Site CRIS-3B. Characterize upper plate basement and fluid flow.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 800 mbsf. • Conduct wireline logging or LWD/LWC and 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-11A

Priority:	Alternate
Position:	8.665716°N, 84.041104°W
Water depth (m):	200
Target drilling depth (mbsf):	1120
Approved maximum penetration (mbsf):	1120
Survey coverage:	BGR 99-7 CMP 1050 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF3**) • Location map (Fig. **F2**)
Objective:	Alternate for Site CRIS-4A. Characterize upper plate basement and fluid flow.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 1120 mbsf. • Conduct wireline logging or LWD/LWC and 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-2B

Priority:	Contingency
Position:	8.483674°N, 84.130675°W
Water depth (m):	2000
Target drilling depth (mbsf):	800
Approved maximum penetration (mbsf):	800
Survey coverage:	BGR 99-7 CMP 4650 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF4**) • Location map (Fig. **F2**)
Objective:	Penetration of décollement at shallow level, fluid flow regime, oceanic crust.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 800 mbsf. • Conduct wireline logging or LWD/LWC.
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia, and basaltic flows

Site summaries (continued)

Proposed Site CRIS-9A

Priority:	Contingency
Position:	8.488790°N, 84.128218°W
Water depth (m):	2000
Target drilling depth (mbsf):	800
Approved maximum penetration (mbsf):	980
Survey coverage:	BGR 99-7 CMP 4550 • Track map (Fig. AF1) • Seismic profile (Fig. AF4) • Location map (Fig. F2)
Objective:	Alternate for Site CRIS-2B. Penetration of décollement at shallow level, fluid flow regime, oceanic crust.
Drilling and logging program:	• APC to refusal, then XCB to 500 mbsf. • RCB from 490 to 980 mbsf. • Conduct wireline logging or LWD/LWC.
Nature of rock anticipated:	Sediments: mud and silt, mud-supported breccia, and basaltic flows

Site summaries (continued)

Proposed Site CRIS-1A

Priority:	Contingency
Position:	8.428579°N, 84.157838°W
Water depth (m):	2115
Target drilling depth (mbsf):	320
Approved maximum penetration (mbsf):	350
Survey coverage:	BGR 99-7 CMP 5740 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF5**) • Location map (Fig. **F2**)
Objective:	Characterize oceanic input to the subduction zone.
Drilling and logging program:	• APC to refusal, then XCB to basement. • RCB from 120 to 320 mbsf. • Conduct wireline logging or LWD/LWC.
Nature of rock anticipated:	Sediments: mud, silt, and basaltic flows

Site summaries (continued)

Proposed Site CRIS-7A

Priority:	Contingency
Position:	8.423031°N, 84.160568°W
Water depth (m):	2120
Target drilling depth (mbsf):	310
Approved maximum penetration (mbsf):	310
Survey coverage:	BGR 99-7 CMP 5850 • Track map (Fig. **AF1**) • Seismic profile (Fig. **AF5**) • Location map (Fig. **F2**)
Objective:	Alternate for Site CRIS-1A. Characterize oceanic input to the subduction zone.
Drilling and logging program:	• APC to refusal, then XCB to basement. • RCB from 110 to 200 mbsf. • Conduct wireline logging or LWD/LWC.
Nature of rock anticipated:	Sediments: mud, silt, and basaltic flows

Figure AF1. Track map for proposed primary and alternate Sites CRIS-1A, CRIS-2B, CRIS-3B, CRIS-4A, CRIS-7A, CRIS-9A, CRIS-10A, and CRIS-11A. Black lines = seismic reflection BGR99 profiles. Red line = BGR99-7.

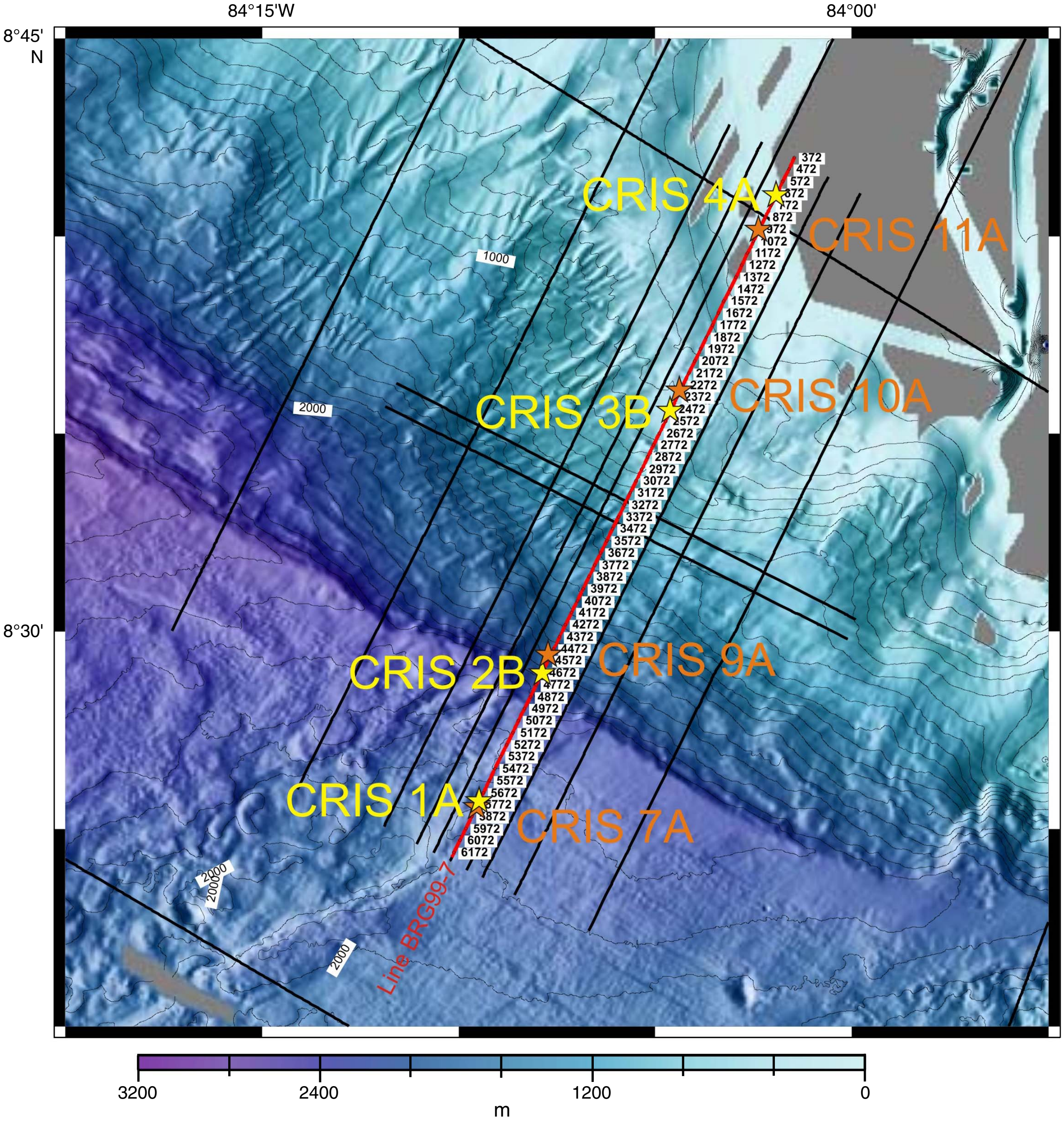


Figure AF2. Proposed primary Site CRIS-3B (alternate Site CRIS-10A).

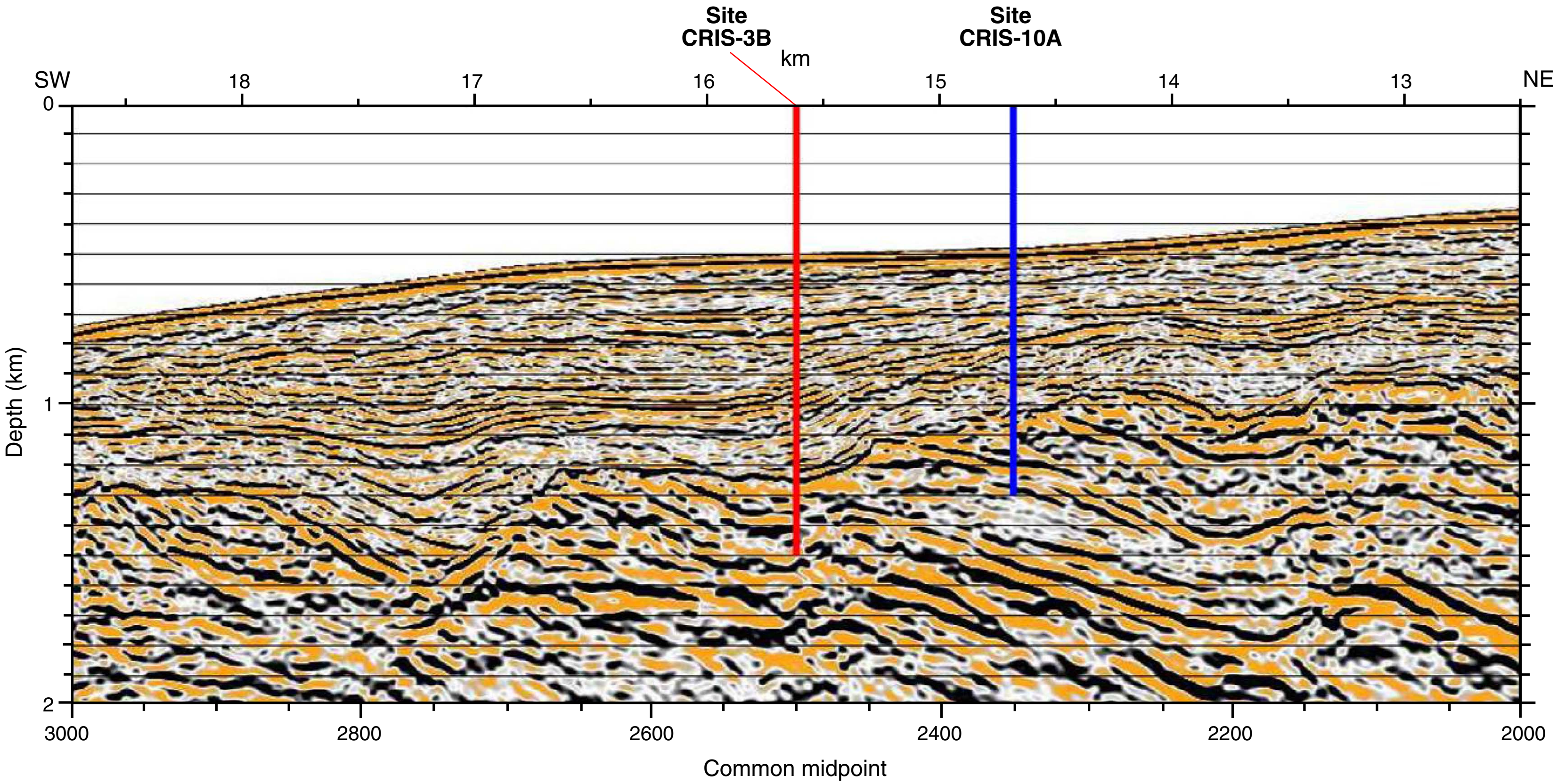


Figure AF3. Proposed primary Site CRIS-4A (alternate Site CRIS-11A).

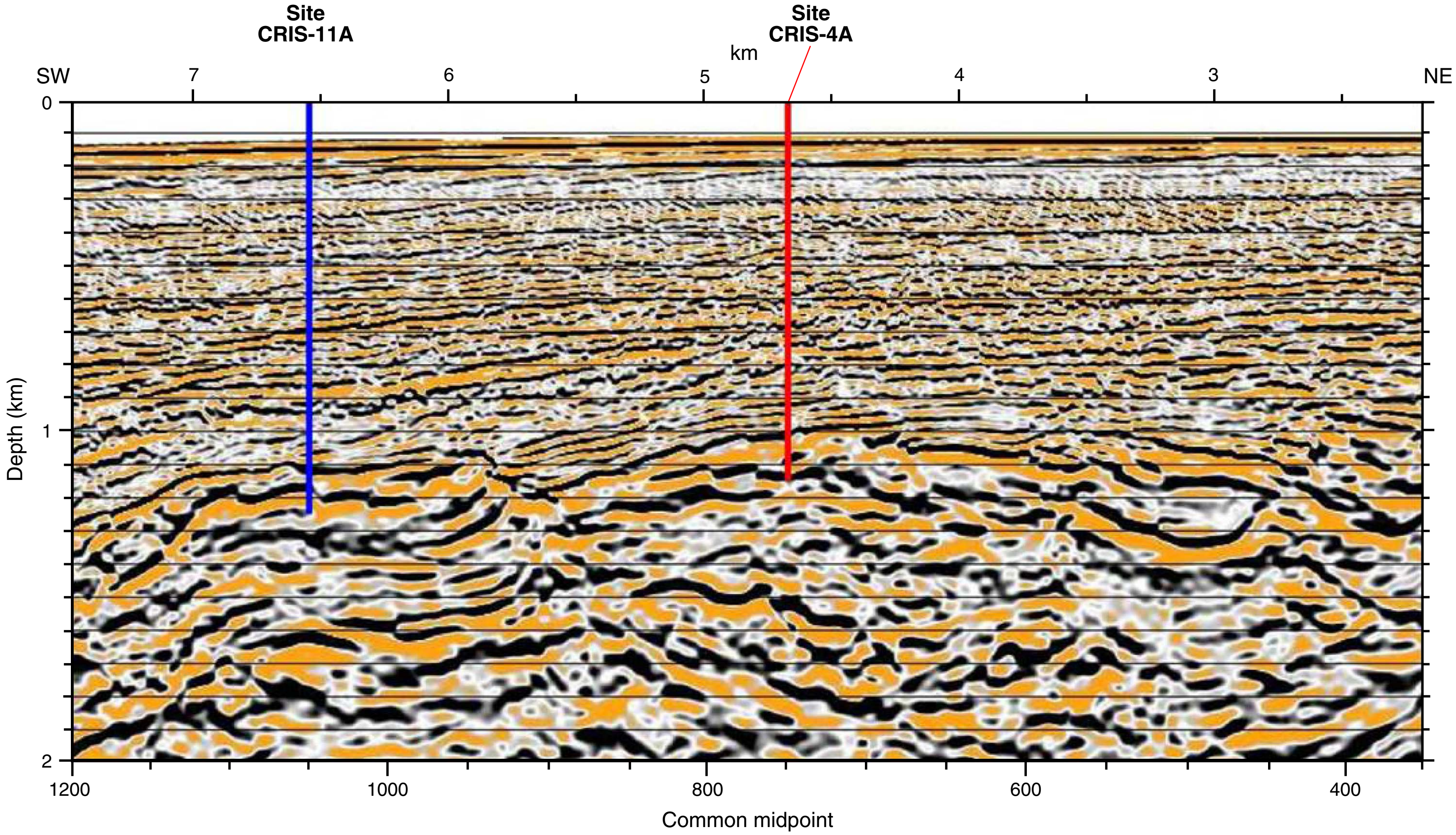


Figure AF4. Proposed contingency Site CRIS-2B (alternate Site CRIS-9A).

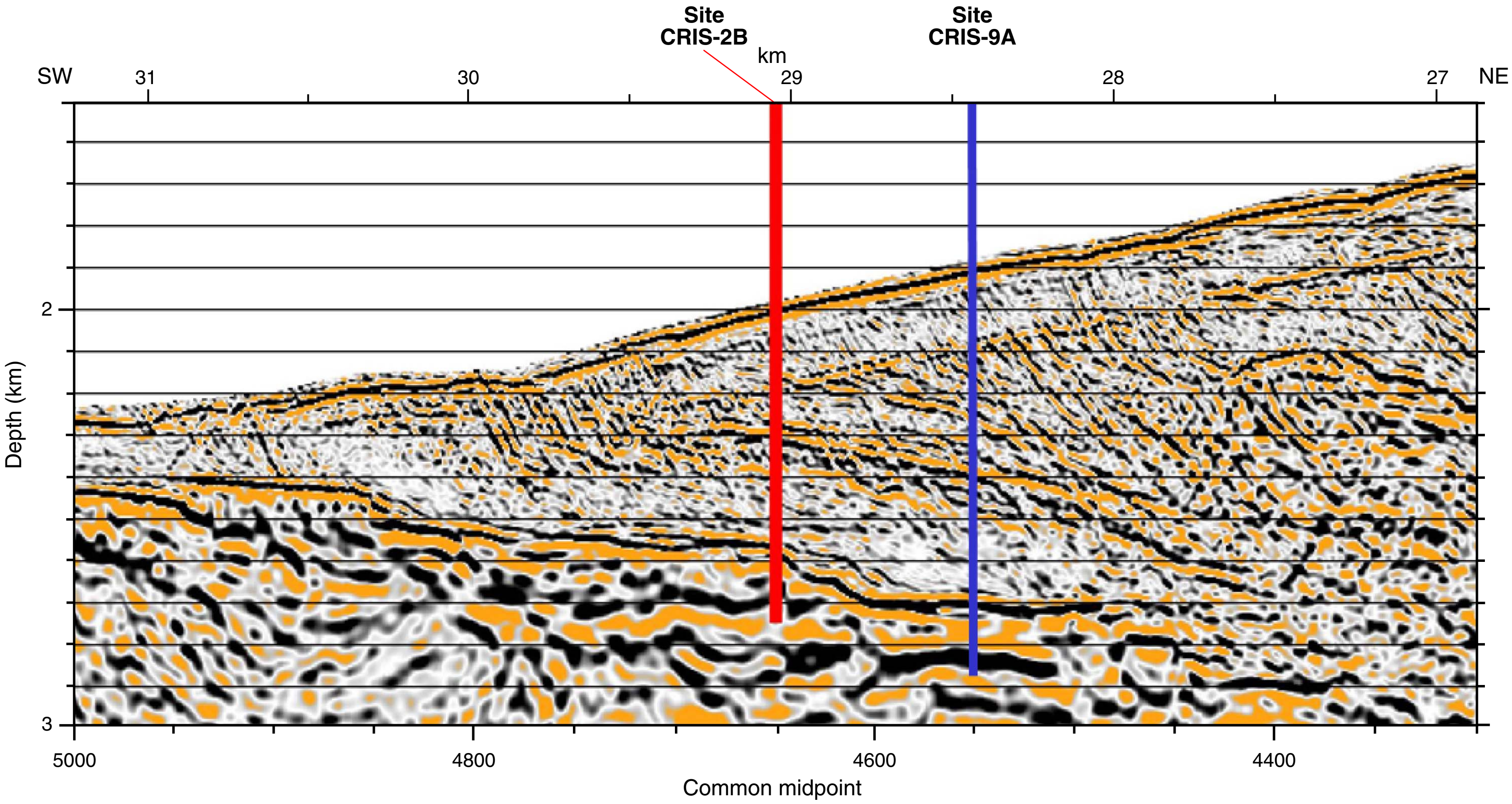
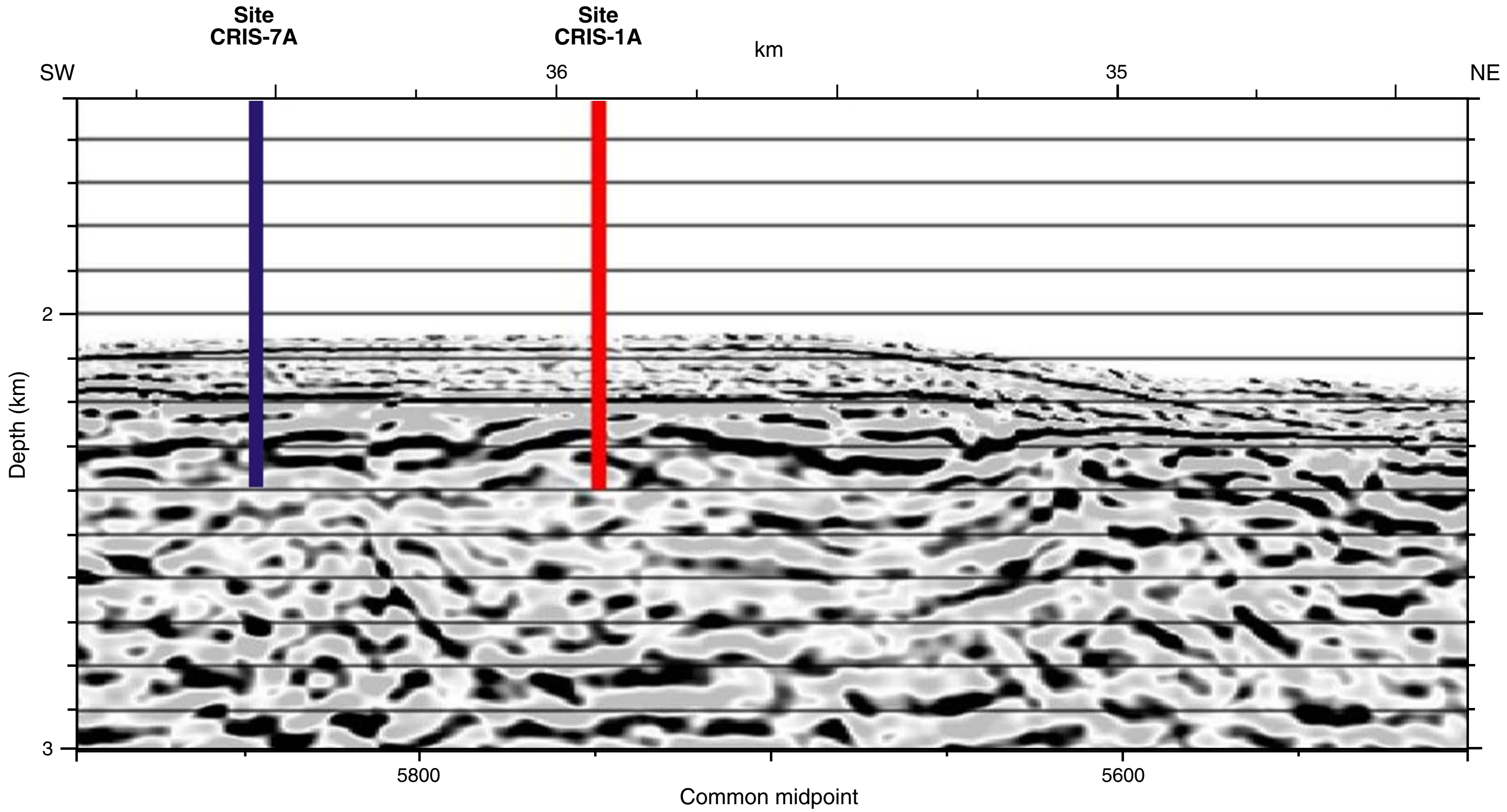


Figure AF5. Proposed contingency Site CRIS-1A (alternate Site CRIS-7A).



Expedition scientists and scientific participants

The current list of participants for Expedition 334 can be found at **iodp.tamu.edu/scienceops/precruise/costarica/participants.html.**