OCEAN DRILLING PROGRAM

LEG 205 SCIENTIFIC PROSPECTUS

FLUID FLOW AND SUBDUCTION FLUXES ACROSS THE COSTA RICA CONVERGENT MARGIN: IMPLICATIONS FOR THE SEISMOGENIC ZONE AND SUBDUCTION FACTORY

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PUBLISHER'S NOTES
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This Scientific Prospectus is based on precruise JOIDES panel discussions and scientific input from the designated Co-chief Scientists on behalf of the drilling proponents. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-chief Scientists and the Operations Manager that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Science and Operations Committees (successors to the Planning Committee) and the Pollution Prevention and Safety Panel.

Technical Editors: Karen K. Graber and Lorri L. Peters

ABSTRACT

The character of the incoming plate subducting at convergent margins and the processes affecting it as it passes below the shallow forearc may play a major role in the nature and extent of hazardous interplate seismicity, as well as the magnitude of volcanism and chemistry of lavas produced in the overlying volcanic arc. The fate of incoming sediments and ocean crust and of their associated volatiles as they pass through the shallow levels of a subduction zone (0-50 km depth) has profound effects on the behavior of the seismogenic zone, which produces most of the world's destructive earthquakes and tsunamis. Fluid pressure and sediment porosity influence fault localization, deformation style and strength, and may control the updip limit of the seismogenic zone. Fluids within both fault zones and sediments underthrust at the trench affect early structural development and are a key agent in transport of chemical species. The mineralogy and chemistry of any subducted sediments and their dehydration reactions during subduction may control the physical properties of the deeper subduction interface and, hence, the updip and downdip limits of the seismogenic zone wherein interplate earthquakes are generated.

Science objectives for Leg 205 have two primary foci. The first is the igneous and alteration history of the basement at reference Site 1039R on the incoming plate. The second is characterizing and monitoring the three hydrological systems: in basement at Site 1039R, in the uppermost section of the subducting sediment section at Site 1040R, and along the décollement and upper conduit at Site 1040R. These goals will be accomplished by (1) limited coring of selected intervals, (2) downhole temperature measurements, (3) logging at Site 1039R, and (4) installation of long-term observatories (CORKs) to monitor temperature and pressure and to sample fluids and gases in each of the hydrologic systems. Time series of fluid composition in the sealed-off intervals will be obtained by using osmotic fluid samplers. These samplers will be recovered for analysis of the water samples 1 to 2 yr postinstallation.

Science objectives for Site 1039R are: (1) quantifying the amount of carbonate in the subducting sediment and uppermost altered basaltic crust to evaluate carbon recycling through the arc; (2) determining the distribution of metalliferous carbonates above the sill and above basement to construct element fluxes into the trench and to constrain their flux out of the basement; (3) determining the extent of sill emplacement and their contribution to the bulk composition of the

subducting igneous crust; (4) determining the igneous and alteration mineralogy, petrology, and geochemistry in the uppermost 100 m of the upper crust and determining subduction fluxes therefrom; (5) determining physical properties in the core and borehole, relevant to fluid flow and deformation such as porosity, density, permeability, fracture distribution, orientation, and strength; and (6) installing a modified CORK within the cored upper basement section to sample fluids and to monitor temperature and pressure.

Science objectives for Site 1040R are: (1) determining physical properties of the décollement horizon from structural experiments on whole-round samples to constrain hydrological modeling and permit integration of fluid flow and deformation models; (2) determining chemistry of pore fluid profiles from décollement whole rounds to compare with profiles measured during Leg 170 and to evaluate possible heterogeneity; (3) determining pressure, temperature, and composition of fluids and gases along the décollement and evaluating any possible changes through time for hydrologic modeling; (4) using selected elements, element ratios, and isotopic compositions in the fluids from the décollement in an attempt to constrain dehydration reactions at the updip and, perhaps, downdip limits of the seismogenic zone; (5) installing three modified CORKs: one to sample fluids and monitor temperature and pressure in the uppermost underthrust sediments and two in the décollement; (6) determining pressure, temperature, and fluid composition in the zone of compaction dewatering beneath the décollement to constrain pathways of fluid return to the surface and to evaluate the effects of this flow system on element fluxes; and (7) collecting whole-round samples from the décollement under appropriate conditions for postcruise microbiological investigations to determine the resident microbial ecology of the zone for comparison with eventual microbial experiments on fluids collected from the décollement.

INTRODUCTION

The character of the incoming plate subducting at convergent margins and the processes affecting it as it passes below the shallow forearc may play a major role in the nature and extent of hazardous interplate seismicity as well as the magnitude of volcanism and chemistry of lavas produced in the overlying volcanic arc. The fate of incoming sediments and ocean crust, and of their associated volatiles, as they pass through the shallow levels of a subduction zone (0-50 km depth) has profound effects on the behavior of the seismogenic zone, which produces most of the world’s destructive earthquakes and tsunamis. Fluid pressure and sediment porosity influence fault localization, deformation style and strength, and may control the updip limit of the seismogenic zone (e.g., Scholz, 1998; Moore and Saffer, 2001). Fluids within both fault zones and sediments underthrust at the trench affect early structural development and are a key agent in transport of chemical species. The mineralogy and chemistry of any subducted sediments and their dehydration reactions during subduction may control the physical properties of the deeper subduction interface and, hence, downdip limits of the seismogenic zone.

The escape of fluids to the surface from depth (return flow) supports a deep biosphere, contributes methane for gas hydrate formation, affects seawater chemistry for selected elements, and is intimately linked to deformation, faulting, and the evolution of the décollement. The distillation and loss of some volatiles and fluid-soluble elements from the shallow slab not only record reactions and processes within the seismogenic zone, but they also play a central role in the supply of residual volatiles to the deeper Earth and change the composition of the slab delivered to the depths of magmatism beneath volcanic arcs. Processes operating in the shallow subduction zone thus affect the way the slab contributes to continent-building magmatism, explosive volcanism, ore formation and, ultimately, the evolution of the mantle through time (collectively known as the subduction factory in many geoscience planning efforts). The subduction signature recorded in the chemistry of arc volcanics constrains the nature and sometimes the volume of the sediments transported through the seismogenic zone to the depths of magmatism. The arc thus acts as a flow monitor for the transport of sediments to depths greater than those that can be drilled or imaged seismically.

The Ocean Drilling Program (ODP) has identified deformation at convergent margins, fluid flow in the lithosphere, and subduction zone geochemical fluxes as important aspects of the JOIDES Long Range Plan (1996). The Initial Science Plan for the Integrated Ocean Drilling Program (IODP) includes an initiative focused on the seismogenic zone. The Central American convergent margin (see Fig. 1) has been a focus area for a number of national and international programs studying the seismogenic zone and subduction factory for several reasons. First, it is one of the few modern subduction zones that is subducting a significant carbonate section and thus provides an opportunity to investigate CO_2 cycling through convergent margins. Second, along strike from Nicaragua to Costa Rica, the style and extent of seismicity and plate coupling changes. Third, along the same section, the style of arc volcanism changes as do volumes and the chemistry of the arc lavas. Changes in both the seismicity and volcanic chemistry have been proposed to result from changes in the balance between sediment underplating, erosion, and subduction (collectively referred to here as sediment dynamics), perhaps related to changing bathymetry, thermal structure, and hydrological behavior along the margin.

Leg 205, building on Leg 170 coring and logging while drilling at the same sites, is designed to investigate the thermal structure and hydrological activity of the Costa Rica segment through a combination of downhole measurements and long-term sampling of fluids as well as monitoring of fluid pressure and temperature at critical horizons. First observations of temporal variations of fluid and gas chemistry will be available once the fluid samples has been recovered about 1 yr postcruise. During the leg, we will also drill and core a minimum of 100 m into the subducting altered oceanic crust to characterize those basement fluxes to the volcanic arc. Once completed, Costa Rica will be the first convergent margin for which drilling-based studies of subducting sediment and basaltic crust, sediment dynamics, forearc structure, and prism hydrology and deformation can be linked to both an active volcanic arc as well as a hazardous seismogenic zone.

BACKGROUND

A large body of work shows that there are differences in seismicity and arc magmatism along the length of the Central American margin, with sharp contrasts seen between Nicaragua and immediately adjacent parts of Costa Rica. The Nicoya section of the Costa Rica margin appears to have M_w = 7 or greater earthquakes at a 40- to 50-yr recurrence interval, with the last such event in 1950 (Guendel, 1986). Coupling between the downgoing and overriding plates is estimated from Global Positioning System (GPS) data to be 40%-60% (T. Dixon, pers. comm., 2001) and appears to start ~15 km arcward of the trench. Nicaragua is characterized by a greater frequency of magnitude 7 or larger earthquakes, including the 1992 tsunamogenic earthquake. Geodetic and seismic studies are currently underway.

In the arc volcanics, ^{10}Be data, radiogenic isotopes, and trace element studies of Nicaragua lavas (Tera et al., 1986; Carr et al. 1990; Reagan et al., 1994; Patino et al., 2000) suggest that the entire sediment section is subducting to the depths of magma generation, producing in the lavas a strong signature from the hemipelagic sediments at the top of the incoming sediment section. In contrast, the Costa Rican lavas have a much weaker sediment signature, little contribution from the uppermost hemipelagic sediments of the incoming plate, and a proportionally larger contribution from the basal carbonate section. Such a difference between the two regions could be explained by sediment accretion or greatly enhanced subduction erosion off northwest Costa Rica.

Various workers have suggested that the changing nature of seismicity and arc volcanism may be due to variations in the incoming plate, the fate of incoming sediments as they traverse the forearc of the overriding plate, or a combination of the two. The bathymetry and thermal structure of the incoming plate and the active fluid flow both outboard and inboard of the trench may play a key role in deformation and sediment dynamics across the margin. In addition, differences in origin and chemistry of the subducting oceanic crust may also contribute to changing chemistry of the arc lavas. The nature of the incoming oceanic crust off Nicoya and the active hydrology of the margin are the primary foci of Leg 205.

The Incoming Plate

There are significant variations in the origin, morphology, and thermal structure of the incoming plate through the Nicaragua-Costa Rica segment of the Central American convergent margin (Fig. 1). Offshore Costa Rica, a tectonic boundary separating lithosphere formed at the East Pacific Rise (EPR) from that formed at the Cocos-Nazca spreading center (CNS) was identified using magnetic anomalies (Barckhausen et al., 2001) and confirmed by seismic reflection data. The boundary, called the fracture zone trace, enters the Middle America Trench (MAT) ~20 km south of the ODP Leg 170 drilling area. This means that the drill holes are underlain by crust that formed at the EPR. The crustal age in the Legs 170 and 205 area is ~24 Ma. The lithosphere to the southwest of the fracture zone trace formed at the CNS, and its crustal ages decrease to the southwest. The oldest crust directly at the fracture zone trace is 22.7 Ma, which corresponds to the break-up age of the Farallon plate.

The part of the Cocos plate that is presently being subducted offshore Costa Rica was overprinted by hotspot-related volcanism between 14 and 12 Ma. This is most evident in the area of the Cocos Ridge off southern Costa Rica, but rock samples dredged from seamounts have proven that the overprinting extended at least as far north as the southern tip of the Nicoya Peninsula (Fisher Seamount). It seems possible that the sills encountered at the base of some of the ODP Leg 170 holes, and also observed in nearby seismic reflection profiles, may be related to this volcanic event.

The topography of the incoming plate also changes along the length of the margin (Fig. 2) (Ranero et al, 2000b). The crust subducting beneath Nicaragua, formed at the East Pacific Rise, is pervasively faulted with offsets of up to 500 m (Kelly and Driscoll, 1998). Off central and southern Costa Rica the ocean plate formed at the Galapagos spreading center has thicker crust and is covered 40% with large seamounts (von Huene et al., 2000; Barckhausen et al., 2001). In the area of ODP Legs 170 and 205, the subducting plate is the smoother segment of ocean crust formed at the EPR, with shallower grabens than those off Nicaragua.

Heat flow studies and coring on the Cocos plate reveal that heat flow offshore the Nicoya Peninsula and to the north averages 30 mW/m^2, significantly lower than values of ~108 mW/m^2 expected for 20-25 Ma crust. The regionally depressed heat flow has been interpreted as evidence for vigorous fluid flow within the upper oceanic crust, which effectively refrigerates the incoming plate by advection (e.g., Langseth and Silver, 1996). Recent heat flow surveys (E. Silver and A. Fisher, pers. comm., 2001) reveal a more complex pattern of vigorous fluid flow in shallow portions of the incoming crust, with local heat flow highs as well as anomalously low values.

There are some parameters that vary little along the entire section shown in Figure 1. The convergence direction is constant with the subducting plate dipping to the northeast. The convergence rate changes only slightly along strike, with a rate of 82 mm/yr off southernmost Nicaragua and 88 mm/yr off southernmost Costa Rica (Kimura, Silver, Blum, et al., 1997). Figure 3 shows that the lithology and thickness of sediment entering the trench is similar at Deep Sea Drilling Project (DSDP) Site 495 (off Guatemala) and ODP Site 1039 (off Costa Rica) and that there is, thus, likely to be little variability in the sediment supply to the trench along the length of the margin.

Leg 170 originally planned basement penetration at Site 1039. This objective was not achieved because of the presence of sills above basement (Kimura, Silver, Blum, et. al., 1997) and the pressure of time needed to satisfy other high-priority Leg 170 objectives. The sills were drillable, but at a slow rate of penetration on a worn rotary core barrel (RCB) bit. For Leg 205, drilling and coring the sills plus a minimum of 100 m penetration into basement remains a highest-priority goal. The extent to which hotspot-related volcanism may have overprinted the EPR signature of the plate subducting beneath northern Costa Rica is an important issue. Some chemical changes in arc lavas between Nicaragua and Costa Rica have been attributed to the presence of more enriched mantle because of Galapagos hotspot volcanism beneath Costa Rica (Carr et al., 1990). If a hotspot chemical signature resides in the subducting oceanic crust, the role of a heterogeneous mantle wedge along the length of the Middle America arc (and geodynamic inferences that follow therefrom) may need closer scrutiny.

Moreover, little is known about the contributions from the altered oceanic crust to arc magmatism and long-term evolution of the mantle, although much work has focused on the role of sediment recycling (e.g., Kay, 1980; Tera et al., 1986; Morris et al., 1990; Plank and Langmuir, 1998). For many key tracer elements in volcanic arc lavas (e.g., K, Sr, U, Pb, B, and Li), alteration processes in the oceanic crust contribute a significant part of the budget subducted to the arc. A large fraction of the water and CO_2 that is deeply subducted will reside in veins and disseminated alteration minerals, much within the zone of oxidative alteration in the upper part of the oceanic basement. Constraining the igneous petrology and chemistry of the upper basement, as well as the style, magnitude, distribution, mineralogy, and chemistry of basement alteration is essential for constructing a complete mass balance for the subduction factory, and for the conclusions drawn therefrom.

The Overriding Plate

Extensive work has imaged the structure of the forearc. Limited Leg 170 coring, drilling, and seismic data show that the bulk of the Pacific margin is a wedge-shaped high-velocity body probably made of rocks similar to the igneous oceanic rocks cropping out along the coast (Shipley et al., 1992; Kimura, Silver, Blum, et al., 1997; Ranero and von Huene, 2000), which precludes the existence of any significantly large sediment mass being recently accreted. Only a small sediment prism (<10 km wide) is located at the front of the margin wedge. Initially, multichannel seismic (MCS) images were interpreted in terms of sediment accretion to the Costa Rica margin (Shipley et al., 1992). More recently, however, and in the wake of Leg 170 drilling, seismic images have been interpreted to show that basically the entire sediment cover of the ocean plate is currently underthrust beneath the margin and that the frontal sediment prism can store very little, if any, of the incoming material (Kimura, Silver, Blum, et al., 1997; Christeson et al., 1999, 2000; McIntosh and Sen, 2000; Moritz et al., 2000; Silver et al., 2000; Ranero et al., 2000a; von Huene et al., 2000).

Prior to Leg 170, the Nicaragua margin was believed to be a nonaccretionary margin while Costa Rica was believed to be a site of sediment accretion (von Huene and Scholl, 1991; Shipley and

Moore, 1986; Shipley et al., 1992). Leg 170 drilling and subsequent research show no current or recent frontal sediment accretion off Costa Rica. The sediment section beneath the décollement at Site 1040 repeats the complete lithology and sequence of the incoming section cored at Site 1039 (Fig. 3), allowing little sediment accretion to the front of the prism at present (Kimura, Silver, Blum, et al., 1997). The thinning of the underthrust section seen between Sites 1039 and 1040 (Fig. 4) must be because of compaction and dewatering. Cosmogenic ^{10}Be, which decays with a 1.5-Ma half life, also shows that there has been little, if any, frontal accretion at this site over the last several million years (Fig. 5) (Morris et al., in press). Surface sediments have very high ^{10}Be concentrations, which decay exponentially with increasing depth and age in the sediment column. The very high ^{10}Be concentrations in the incoming sediment section beneath the décollement are typical of young marine sediments. Were these incoming sediments to be frontally accreted, the prism sediments above the décollement would have measureable ^{10}Be enrichments. The very low concentrations in the sediments above the décollement indicate that they are older than several million years and preclude construction of the prism from accretion of imbricate thrust packets over the last several million years. The prism is thus either a paleoaccretionary prism or is composed largely of slumped slope sediments rather than accreted marine sediments. In the absence of recent frontal accretion, the thinning of the underthrust hemipelagic sediments observed between Sites 1039 and 1040 must be because of dewatering and compaction.

The sediment signature in the arc lavas suggests complete sediment subduction to the depths of magma generation beneath Nicaragua, with only a limited sediment signature in the Costa Rica lavas. The seismic and lithologic observations indicate complete sediment subduction past the prism front in both regions. The arc and prism observations can be reconciled if sediments are underplated to the base of the prism beneath Costa Rica or if greatly enhanced subduction erosion occurs beneath the Nicoya segment.

There is evidence for underplating to the base of the prism landward of the Legs 170 and 205 coring area. Christeson et al. (1999) use seismic reflection and refraction data to show stacked velocity duplicates, interpreted as repeated stratigraphic sections because of underplating. The low, but real, ^{10}Be enrichments in the Costa Rican lavas could be explained if the upper 80-100 m of the incoming sediment section were underplated (Valentine et al., 1997).

In addition to evidence for sediment subduction and underplating beneath the Nicoya segment, the seismic stratigraphy of the slope off Nicaragua and the tectonic structure off Costa Rica indicate extension and subsidence of the margin during much of the Miocene (Ranero et al., 2000a; Ranero and von Huene, 2000; Walther et al., 2000). Multibeam bathymetry along the continental slope displays structures that indicate significant mass wasting off Nicaragua and a rugged morphology off Costa Rica (Ranero et al., 2000a, von Huene et al., 2000), which is consistent with tectonic erosion and thinning of the overriding plate. These results are further substantiated by Leg 170 coring and postcruse science. Coring at Site 1042, 7 km landward of the Middle America Trench, encountered a ~30-m-thick sequence of fossiliferous well-lithified calcarenite breccia at a depth of~4000 meters below sea level (mbsl) (Kimura, Silver, Blum, et al., 1997). Fossil, textural, cement paragenesis, and sedimentological observations document that the calcarenite was formed, brecciated, and cemented in a nearshore setting (Vannucchi et al., 2001). Sr isotope ratios place the depositional age at 16-17 Ma—latest early Miocene—and establish that the breccia section is stratigraphically upright. It is overlain by ~320 m of unconsolidated slope mud showing the complete Pleistocene to Miocene sequence where benthic foraminifers indicate the subsidence of the margin from the upper bathyal to abyssal depths (Meschede, 1999; Vannucchi et al., 2001). Unfortunately, erosion rates over the last several million years are not well constrained. Speculation is that tectonic erosion has been controlled by the roughness of the subducting plate. The thinning of the overriding plate and the continental margin morphology suggests that subduction erosion increases in intensity from Nicaragua to southern Costa Rica (Ranero and von Huene, 2000).

For the purposes of Leg 205, an important result is that the margin off Nicoya is not currently accreting sediments and has not done so over the last several million years. The conclusion that all sediments fed to the trench over this time frame have been subducted past Site 1040 greatly simplifies estimating the mass and element fluxes. Specifically, changes in underthrust sediment thickness between Site 1039 and 1040 are due to compaction. To calculate the flux of elements out of the compacting sediment section and updip from the deeper décollement, steady-state conditions may be assumed.

Margin Hydrology

At the Costa Rican subduction zone, coring during ODP Leg 170 and subsequent postcruise studies have identified three fluid-flow systems: active flow of modified seawater within the upper oceanic crust, updip fluid flow within underthrust sediments, and deeply sourced fluid expulsion along the décollement and through the margin wedge (e.g., Silver et al., 2000; Kastner et al., 2000).

The existence of active fluid flow in the oceanic basement of the incoming plate is evidenced by both the heat flow anomalies discussed earlier and the chemistry of pore fluids sampled during Leg 170. Postcruise studies of pore fluid chemistry (Fig. 6A) show chemical characteristics (e.g., $^{87}Sr/^{86}Sr$) typical of modern seawater in the uppermost sediments. Below this, values depart increasingly from seawater at increasing depth as a result of diagenesis. The deepest sediments, however, have pore fluid chemistry that trends back toward modern seawater values, particularly evident in the Sr isotope profile. The heat flow anomaly and pore fluid profiles have been modeled in terms of active fluid flow at rates of ~1-5 m/yr. While certainly model dependent, these results do indicate extensive contemporary flow of seawater to basement and require high permeability horizons, thought to be within the uppermost basement based on results from off-axis drilling along the Juan de Fuca and Mid Atlantic Ridges (Davis and Becker, 1994; Becker et al., 1997, 1998; Fisher, 1998; Davis et al., 2000; Kopf et al., 2000). In addition to cooling the uppermost part of the plate, the flow may further alter the basaltic crust. Subducted high-permeability horizons may provide conduits for fluids leaving the deeper subduction zone.

The décollement and faults cutting through the margin wedge of the upper plate serve as pathways for updip flow of deeply sourced fluids. Structural observations across the décollement indicate a zoned fault, with heavily fractured fault rocks above a ductile, plastic zone that may act as an aquitard to segregate the flow systems above and below the plate boundary (Vannucchi and Tobin, 2000; Tobin et al., 2001). Pore fluid chemistry studies since Leg 170 show that fluids sampled along the décollement zone at Sites 1040 (320-360 meters below seafloor [mbsf]) and 1043 (~130-150 mbsf) have distinct chemical signatures indicative of focused fluid advection. Similar chemical anomalies are also seen in an upper conduit at Site 1040 (~180-200 mbsf), which may occur along a thrust fault. Extremely high Li concentrations are observed along the thrust and décollement at Site 1040 (Fig. 6B). Enrichments in Ca and Sr, changing Sr and Li isotopic compositions, as well as higher concentrations of thermogenic heavy hydrocarbons C_3-C_6) are also observed. Collectively, these data indicate that some fraction of the fluids sampled along these localized horizons are derived from depths great enough that temperatures are ~150°C. This temperature corresponds to the updip limit of the seismogenic zone (e.g., Hyndman and Wang, 1993; Hyndman et al., 1997). The sharpness of the pore fluid anomalies at these horizons indicates updip advective flow and permits virtually no diffusion or vertical advection away from these intervals. The composition of deeply sourced fluids derived from the updip limit of the seismogenic zone may be useful in constraining the mineralogy of sediments at depth and the dehydration reactions that are thought to be important in governing the rheological properties of the subduction interface in the region of seismogenesis. Given that most seismogenic zones will be forever beyond the reach of even a riser drill ship, development of chemical proxies for "remote sensing" of processes occurring in the seismogenic zone is an important adjunct of Leg 205.

Structural and chemical studies indicate a third hydrologic system, which drains fluids from the underthrust sediment section. Results from Leg 170 documented the complete underthrusting of the incoming sedimentary section at the trench, with the important implication that observed changes in sediment thickness and porosity directly reflect the evolution of effective stress. Laboratory consolidation tests, combined with logging-while-drilling (LWD) data from Leg 170, show that the subducting sediments are effectively undrained at Site 1043 (Saffer et al., 2000; D. Saffer, pers. comm., 2001). At Site 1040, the lower carbonate section (Unit III) remains essentially undrained, whereas the upper hemipelagic units (Units I and II) are partially drained. Pore fluid profiles from sediments immediately below the décollement at Sites 1040 and 1043 show a distinct chemistry from that of the décollement, indicating little, if any, communication between the two hydrologic systems. A Ba spike immediately below the décollement (Fig. 6C) results from sulfate reduction in the uppermost underthusting section that mobilizes Ba out of barite. The very low Ba values in the décollement zone itself indicate that these fluids are not draining into the décollement. Other broad anomalies below the décollement also imply updip advective flow of locally derived fluids (Kastner et al., 2000).

The differences in pore pressure development downsection reflect nonuniform fluid escape. More rapid drainage of the uppermost ~100 m (Units I and II) than of Unit III may result from (1) more abundant coarse-grained high-permeability ash layers that focus flow, (2) higher permeability within the hemipelagic sediments, or (3) significant permeability anisotropy within the hemipelagic sediments. The nonuniform dewatering also has important mechanical implications. An inferred minimum in effective stress developed near the top of Unit III between Sites 1043 and 1040 results in a mechanically weak horizon and suggests that detachments may form below the décollement there. This is consistent with the down-stepping of the décollement at 2-3 km from the trench observed in this region (McIntosh and Sen, 2000) and illustrates the role of fluid pressure in mediating structural development. Based on observed changes in porosity, volumetric fluid sources (in $V_{fluid}/V_{sediment/s}$) range from ~10^{-12} s^{-1} at the top of the section to ~10^{-13} s^{-1} at the base. These values are one to two orders of magnitude larger than those calculated for underthrust sediments at the Nankai and Barbados subduction zones (e.g., Zhao et al., 1998; Screaton et al., in press). This dramatic difference likely reflects higher sediment permeabilities at Costa Rica, resulting in a more active fluid flow system.

Figure 7 shows schematically the three separate hydrologic systems, their locations in the Leg 205 coring area, and summarizes their physical and chemical characteristics. Hydrological and geological modeling (e.g., Saffer et al., 2000; Silver et al., 2000) suggests relatively high permeabilities in the oceanic basement, décollement, and underthusting section.

SCIENTIFIC OBJECTIVES

During Leg 205, we will return to Leg 170 drill sites; the Leg 205 sites are 1039R, 1040R, and alternate Site 1043R. Science objectives for Leg 205 have two primary foci. The first is the igneous and alteration history of the basement at reference Site 1039R on the incoming plate. The second is on the three hydrological systems: in basement at Site 1039R; in the uppermost section of the subducting sediment section at Site 1040R; and along the décollement and upper conduit at Site 1040R. An alternate site, Site 1043R, has the same objectives as those at Site 1040R. These goals will be accomplished as described in detail below by limited coring of selected intervals, downhole temperature measurements, logging at Site 1039R, the installation of long-term observatories to monitor temperature and pressure, and sampling fluids and gases at key hydrological intervals.

Site 1039R Science Objectives

During Leg 205, coring and sampling will begin at Site 1039R within the carbonates above the sill encountered during Leg 170, will continue through the sill and the previously undrilled sediments beneath the sill, and ~100 m into basement. The scientific objectives to be addressed through coring, sample analysis, and logging at Site 1039R are as follows.

1. Quantify the amount of carbonate in the subducting sediment and uppermost altered basaltic crust for comparison with CO_2 fluxes out of the volcanoes to evaluate carbon recycling through the arc.
2. Determine the distribution of metalliferous carbonates above the sill and above basement and determine the concentrations of elements such as Cu, Cr, Ni, V, and Pb to construct element fluxes into the trench and to constrain their flux out of the basement.
3. Determine the extent of sill emplacement and their contribution to the bulk composition of the subducting igneous crust.
4. Determine the igneous and alteration mineralogy, petrology, and geochemistry in the uppermost 100 m of the oxidative alteration zone and characterize the original volcanic structure within the basement. Use the geochemical data to calculate subduction fluxes. Attention will be paid to low-temperature alteration features that may result from near trench fluid flow as well as that deriving from ridge-crest and near off-axis hydrothermal circulation.
5. Determine physical properties in the core and borehole that may affect estimations of basement composition and lithologic variation or that relate to fluid flow and deformation such as porosity, density, permeability, fracture distribution and orientation, and strength.

A long-term borehole observatory (i.e., a modified CORK) will also be emplaced at Site 1039R to sample fluids and to monitor temperature and pressure within the uppermost permeable basement. The science objectives for this are to

1. Use pressure, temperature, fluid, and gas compositions and fluid flow rates together with downhole measurements to characterize the fluid and heat fluxes responsible for the abnormally low heat flow in the vicinity of this site because of seawater incursion to basement.
2. Evaluate the thermal, hydrological, and chemical implications of this extensive fluid circulation for the thermal structure of the uppermost part of the subducting plate, the hydrological pathways available in the shallow subduction zone and overlying prism, and global element fluxes.

Site 1040R Science Objectives

Limited coring through the décollement and into the uppermost underthrust section at Site 1040 and installation of modified CORKs to monitor and sample within the area of maximum flow of deeply sourced fluids in the décollement and in the underthrust sediment section address the following scientific objectives.

1. Determine physical properties of the décollement horizon from further structural experiments on whole-round samples to constrain hydrological modeling and permit integration of fluid flow and deformation models.
2. Determine chemistry of pore fluid profiles from décollement whole rounds to compare with profiles measured during Leg 170 and to evaluate possible heterogeneity.
3. Determine pressure, temperature, and composition of fluids and gases along the décollement and evaluate any possible changes through time for hydrologic modeling. This same data set will constrain the flux of elements out of the downgoing sediment section along the décollement to evaluate the role of fluid egress on element fluxes to the ocean and its corollary, changing composition of the residual slab because of fluid loss.
4. Use selected elements, element ratios, and isotopic compositions in the fluids from the décollement in an attempt to constrain dehydration reactions at the updip and, perhaps, downdip limits of the seismogenic zone.
5. Determine pressure, temperature, and fluid composition in the zone of compaction dewatering beneath the décollement to constrain pathways of fluid return to the surface and to evaluate the effects of this flow system on element fluxes.
6. Collect whole-round samples from the décollement under appropriate conditions for postcruise microbiological investigations to determine the resident microbial ecology of the zone for comparison with eventual microbial experiments on fluids collected from the décollement.

A lower-priority target at Site 1040R is the fluid conduit (perhaps a thrust) encountered at 180-220 mbsf during Leg 170 coring. Pore fluid chemistry profiles across this horizon show advective flow of deeply sourced fluids, similar to those along the décollement. If necessary, the objectives above for the décollement could also be addressed at this horizon.

Alternate Site 1043R Science Objectives

Site 1043R has been approved as an alternate site. Installation of a modified CORK with a sampling interval in the décollement here would accomplish all the décollement science objectives at

Site 1040. Penetrations at both Sites 1040 and 1043 would permit close comparison of hydrological and compositional characteristics along a section of the décollement 1 km apart.

DRILLING STRATEGY

The complete Leg 205 sequence of operations and time estimate is shown in Tables 1 and 2.

Site 1039R

The first site occupied during Leg 205 will be Site 1039R. One hole is planned, which will be partially cored and into which we will install the long-term hydrologic borehole observatory. Our first step will be to wash a reentry cone and 16-1/2-in casing into the seafloor. We will then reenter this hole with the RCB and drill without coring to ~340 mbsf. RCB coring will commence from there through the sill, basal sediments, and ~100 m into basement. This basement coring is intended to obtain the samples required to characterize basement but also to open up the circulating system within the upper basement for the borehole observatory. While drilling/coring, a number of Davis-Villinger temperature probe (DVTP) temperature measurements will be made, as formation conditions permit, to complement existing data. If hole conditions permit, we will log the entire hole with the triple combination tool and the Formation MicroScanner (FMS)/sonic velocity tools. The next step will be to reenter the hole with a larger bit and open the hole up to 14-3/4-in in preparation to install the 10-3/4-in casing. The 10-3/4-in casing will then be emplaced into the hole (with a mud motor and underreamer if necessary) to just above the zone that the observertory will monitor. The casing will be cemented in place to inhibit communciation between the casing and the formation. Next, we will drill out the cement shoe and clean the rat hole with the RCB bit. Then, we will assemble a 4-1/2-in casing screen, casing packer, and casing to the instrument hanger (Fig. 8). Then the entire assembly will be lowered into the hole and latched in to seal the borehole outside of the 4-1/2-in casing. The casing packer will then be inflated to seal off the zone at the bottom of the hole that is targeted for monitoring. Finally, the osmo-sampler with integral temperature sensors will be lowered through the center of, and latched into the bottom of, the 4-1/2-in casing; this will completely seal the zone to be monitored. The final installed configuration for this modified CORK hydrologic borehole observatory is shown in Figure 8. Two absolute pressure gauges including data loggers will be installed within the instrument hanger head: one sensor will sense pressure within the sealed-off fluid sampling zone at the bottom of the hole, the other one will record pressure variations present within the borehole above the sealed-off section. One additional sampling line, running from the instrument hanger head all the way down to the sealed-off zone, will be installed for future pressure/fluid sampling purposes.

We are reviewing the existing drilling and seismic data to determine if we will request permission to relocate Site 1039R closer (0.5 km) to the trench axis. This will have the advantage of minimizing the amount of gabbro sill that will need to be penetrated to reach oceanic crust. However, we will be farther from the known section cored at Leg 170's Site 1039; this may require having to core the entire section if Pollution Prevention Safety Panel (PPSP) permission to drill without coring is not obtained.

Site 1040R

At Site 1040R, we will drill three holes. Each of these holes will be completed with a modified CORK identical to that described for Site 1039R above. Each installation will be designed to monitor a single zone. The first hole will monitor the uppermost underthrust sediments and the second two holes will both monitor the décollement. After installing the reentry cone and 16-1/2-in casing, the first hole at Site 1040R will be washed from 0 to ~180 mbsf and then cored from ~180 to 410 mbsf, penetrating the upper fluid conduit, décollement, and terminating in the upper underthrust sediments. This will help us identify the best place to seat the packer and 10-3/4-in casing shoe and locate the décollement accurately for the next two holes planned at this site. It will also save time as no further cores will need to be taken at this site. During the coring, we anticipate conducting about five temperature measurements to complement existing data. After the 10-3/4-in casing is cemented in place (with the casing shoe below the décollement), the osmo-sampler will be emplaced with the packer seated below the 10-3/4-in casing shoe in the uppermost underthrust sequence.

The second hole at Site 1040R will be identical, with the exception that the casing shoe and packer will be seated just above the décollement and the osmo-sampler emplaced into the décollement to monitor it. Although no cores need to be taken in this and the third hole, we must use the RCB bit to drill out the cement shoe in the bottom of the 10-3/4-in casing so we can core specific horizons in the latter two holes at Site 1040R if required. The third hole will also target the décollement but will be offset by ~100 m.

No logging is planned for any of these holes based on the experience with LWD and drilling at Site 1040 during Leg 190.

Alternate Site 1043R

Site 1043R is an alternate site, at which installing long-term monitoring of fluids in the décollement could be attempted if drilling at Site 1040R fails for any reason. The strategy there would be basically the same as for Site 1040R, with one hole aiming to monitor the underthrust sequence and at least one hole sampling fluid flow within the décollement.

LOGGING PLAN

Because Leg 170 conducted LWD operations where Leg 205 will return, we will have a minimal logging program on this leg. At Site 1039R, we will run the triple combination and FMS/sonic strings to determine physical properties and structures of the lowermost sediments and basement rocks. The triple combination string includes the hostile-environment natural gamma ray sonde (HNGS), accelerator porosity sonde (APS), hostile-environment lithodensity tool (HLDT), and dual induction tool (DIT) and will be deployed with Lamont-Doherty Earth Observatory temperature/acceleration/pressure (LDEO-TAP) tool. The FMS/sonic string includes the FMS, dipole shear sonic imager (DSI) or long-space sonic sonde (LSS). We plan to log the entire section including the shallow portion previously logged with LWD during Leg 170. This will allow comparison to the Leg 170 LWD data as well as some data (e.g., sonic velocity and FMS) types that are not collected by LWD. No logging is planned at Site 1040R because of the difficult borehole environment encountered during Leg 170.

SAMPLING STRATEGY

Sampling guidelines and policy are available at the following Web site URL: http://www odp.tamu.edu/publications/policy.html. The Sample Allocation Committee (SAC; composed of co-chiefs, staff scientist, and ODP curator on shore and curatorial representative on board ship) will work with the entire scientific party to formulate a formal leg-specific sampling plan for shipboard and postcruise sampling. Modification of the strategy during the leg must be approved by the co-chiefs, 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.

As Leg 205 will reoccupy sites cored during Leg 170, only minimal coring will be conducted. At Site 1039R, we will initiate RCB coring from ~50 m above the gabbro sill to provide overlap between Leg 170 and Leg 205 coring results as well as to document pore fluid profiles. RCB cores will be continuously taken through the gabbro sill, the basal sediment section below it, and a minimum of 100 m into basaltic basement. At Site 1040R, cores will be taken from ~180 to 420 mbsf to obtain samples from the upper fluid conduit (thrust), décollment, and uppermost underthrust sequence.

We anticipate extensive whole-round sampling to document pore fluid chemistry profiles, sediment strength, stress and consolidation, and permeability, as well as, potentially, microbiological experiments. In the Site 1039R basement cores, 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.

For parts of the section cored at Site 1039R, there will only be one copy of the section available for core description and sampling. In some critical intervals there may be considerable demand for samples from a limited amount of recovered core material. These intervals may require special handling, a higher sampling density, or reduced sample size. A coordinated sampling plan may be required before critical intervals are sampled.

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FIGURE CAPTIONS

Figure 1. ODP Leg 205 Costa Rica drilling area including isochrons derived from mapped seafloor magnetic anomalies (from Barckhausen et al., 2001). Numbers indicate crustal ages in million years. Tectonic boundaries, locations of DSDP Leg 84 and ODP Leg 170 drill sites, as well as arc volcanoes (triangles) are shown. FS = Fisher Seamount, QSC = Quesada Sharp Contortion, MAT = Middle America Trench.

Figure 2. Bathymetry of the ODP Leg 205 Costa Rica drilling area (Ranero et al., 2000b), showing the Leg 170 and the proposed Leg 205 drill sites. Line marks two coinciding multichannel seismic lines (line CR-20, Shipley et al., 1992; line BGR-99-44, C. Reichert and C. Ranero, pers. comm., 2001).

Figure 3. Summary plots of recovered lithology during Leg 170 at Sites 1039, 1040, and 1043, with lithology of DSDP Site 495, on the incoming plate outboard of Guatemala, for comparison. Note the similarity of incoming sediment sections at Sites 1039 and 495, as well as the repetition of Site 1039 sequence and lithology below the décollement at Sites 1040 and 1043. Lithologic columns modified from Kimura et al., 1997.

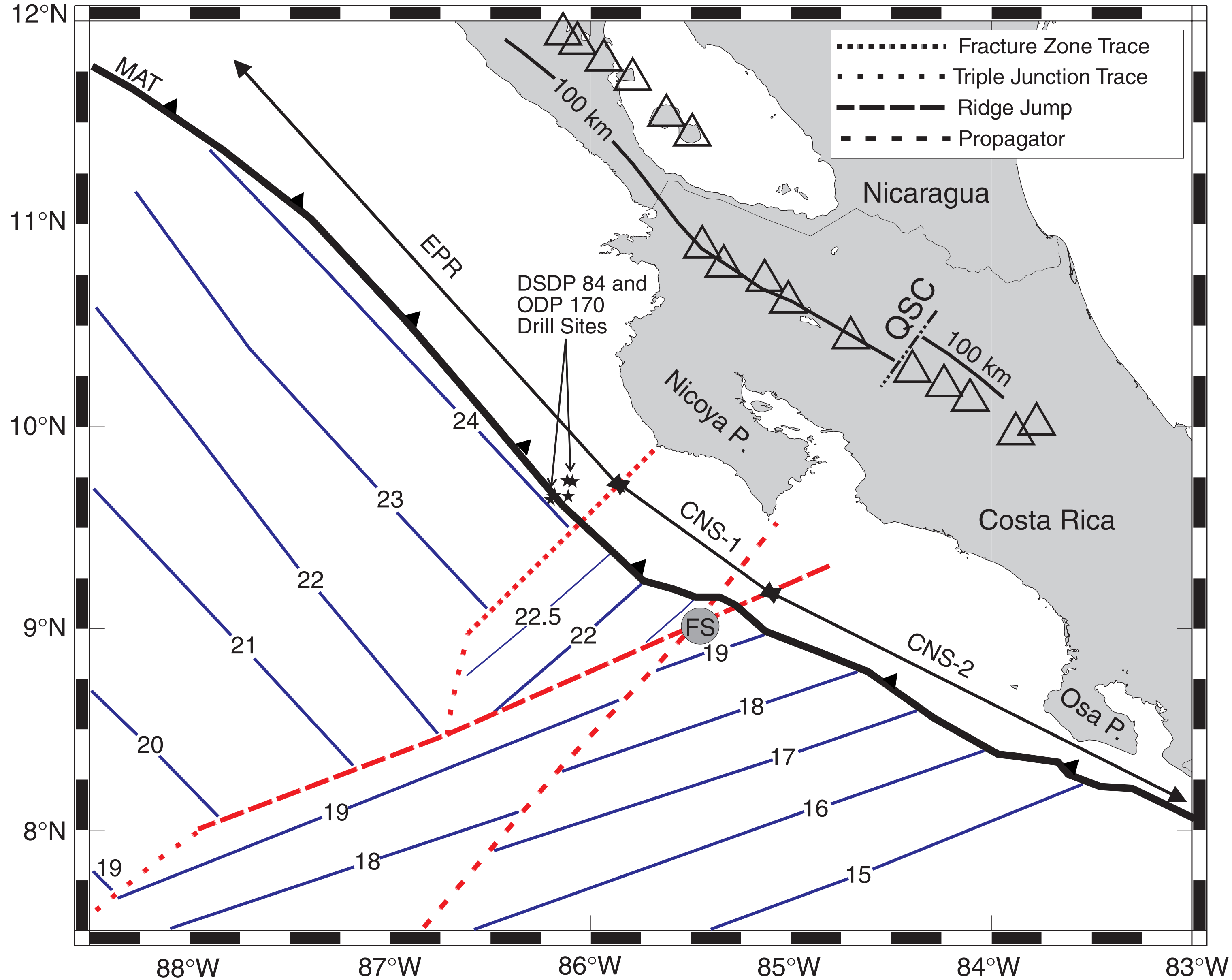
Figure 4. A. Depth-migrated multichannel seismic line CR-20 across proposed Leg 205 drill sites (Stoffa et al., 1991; Shipley et al., 1992). Positions of proposed Leg 205 drill sites are identical to positions of the Leg 170 Sites 1039, 1040, and 1043. **B.** Post-stack time-migrated multichannel seismic line BGR-99-44 (processing by C. Ranero, GEOMAR, Kiel, Germany) across proposed Leg 205 drill sites (C. Ranero and C. Reichert, pers. comm., 2001). Positions of proposed Leg 205 drill sites are identical to positions of Sites 1039, 1040, and 1043 cored during Leg 170. CDP = common depth point.

Figure 5. Plot of cosmogenic ^{10}Be vs. depth in sediment column at Site 1040. Made by cosmic rays in the atmosphere and decaying with a 1.5-m.y. half-life, measurable ^{10}Be enrichments are seen in sediments younger than 7-10 Ma. The underthrust sediments beneath the décollement have high values typical of the incoming sediment section. Throughout the prism sediments of the upper plate, ^{10}Be concentrations are very low, typical of sediments that are older than 3-5 Ma.

Figure 6. **A.** Strontium isotope ratios from pore water samples from Site 1039 are indicated by the solid line, with the dashed line showing the Sr seawater curve appropriate to the sediment age. Note the basal pore water trend toward modern seawater composition, with values greater than Miocene seawater, indicating a strong seawater component in basement fluids. **B.** High lithium concentration in pore water samples from the décollement and fluid conduit at Site 1040; see text for discussion of correlative indicators of higher-temperature (>110°-150°C) deeply sourced fluids advecting from depth along the décollement and upper conduit. **C.** Barium concentration in pore water samples in the uppermost part of the underthrust section from Site 1040; high pore water Ba concentrations from sulfate reduction have not diffused or advected into the décollement, indicating a separate fluid flow regime in the underthrust sediments.

Figure 7. Schematic illustration of physical and chemical characteristics of the three distinct hydrological systems in the Legs 170 and 205 area. Figure courtesy of D. Saffer and based on Saffer et al., 2000 and Silver et al., 2000.

Figure 8. **A.** Schematic of the proposed modified CORK for Site 1039R. **B.** Schematic of the proposed modified CORK for Site 1040R underthrust sequence. **C.** Schematic of the proposed modified CORK for Site 1040R décollement system. ROV = remotely operated vehicle.



Fracture Zone Trace
Triple Junction Trace
Ridge Jump
Propagator
MAT
EPR
100 km
100 km
Nicaragua
Costa Rica
QSC
Nicoya P.
Osa P.
DSDP 84 and
ODP 170
Drill Sites
CNS-1
CNS-2
FS
24
23
22.5
22
22
21
20
19
19
19
18
18
17
16
15
12°N
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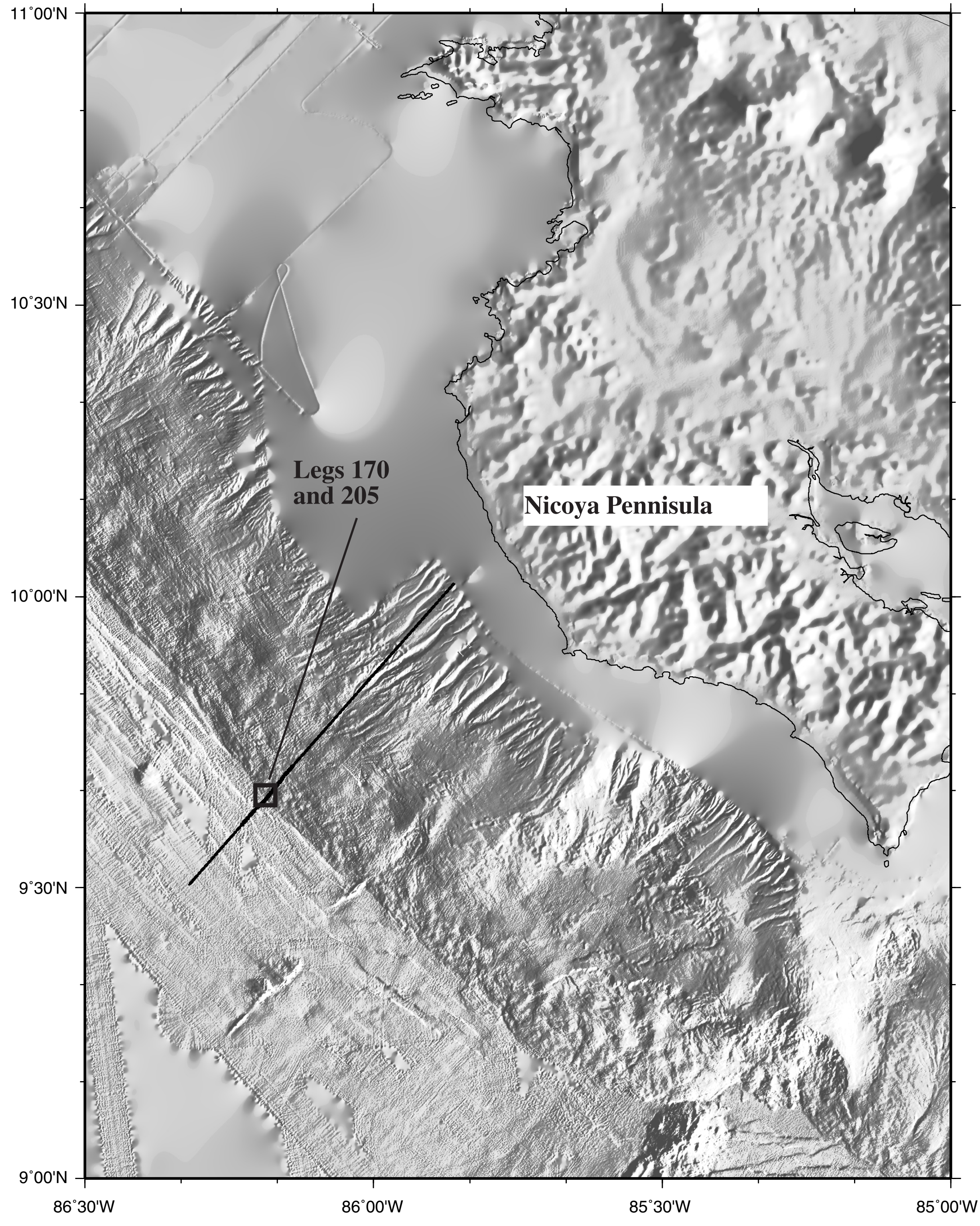
87°W
86°W
85°W
84°W
83°W

Figure 1


11°00'N
10°30'N
10°00'N
9°30'N
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86°30'W
86°00'W
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85°00'W
Legs 170
and 205
Nicoya Pennisula

Figure 2

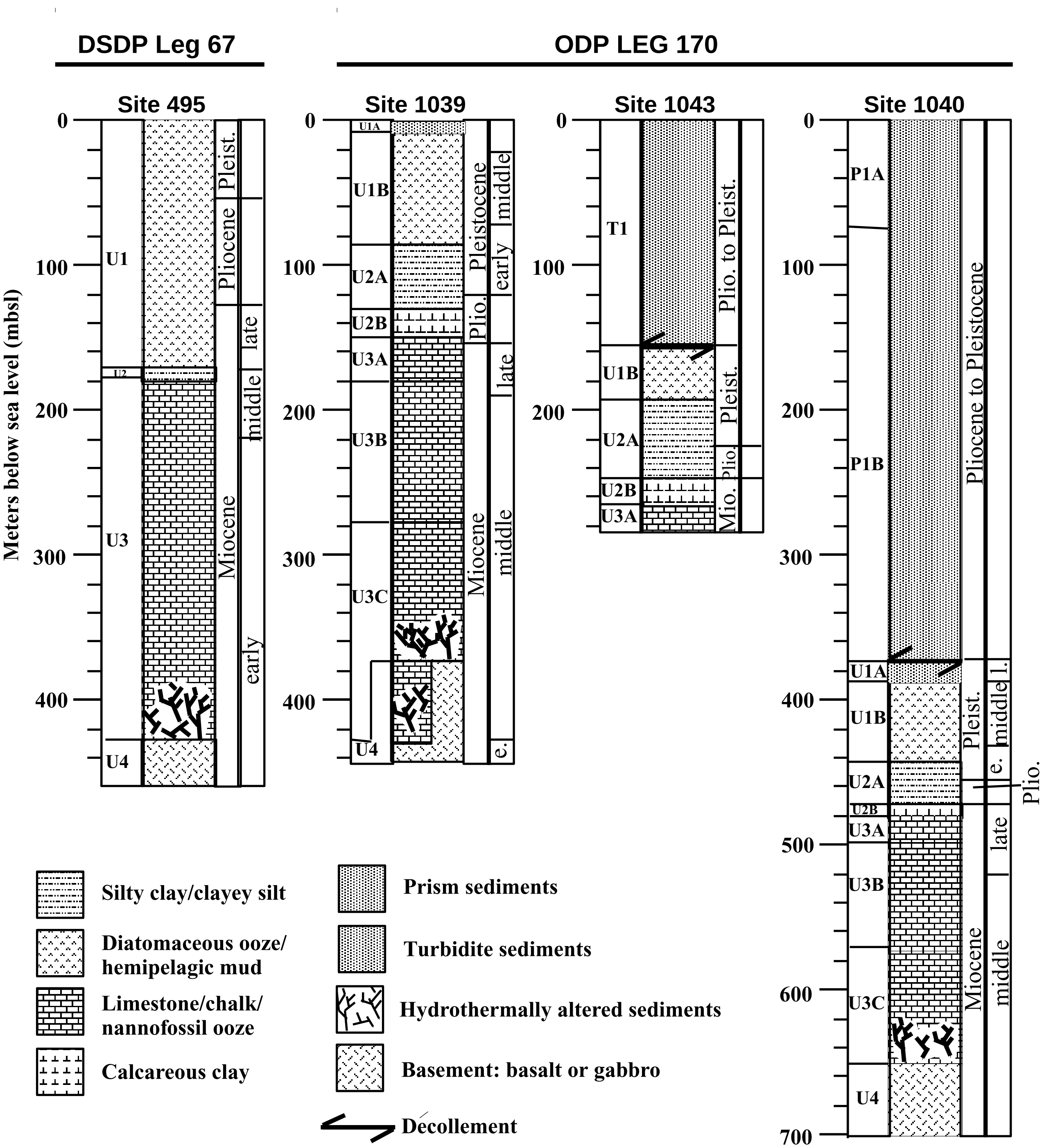
DSDP Leg 67
ODP LEG 170
Site 495
Site 1039
Site 1043
Site 1040
Meters below sea level (mbsl)
0
100
200
300
400
500
600
700
U1
U2
U3
U4
U1A
U1B
U2A
U2B
U3A
U3B
U3C
T1
P1A
P1B
Pleist.
Pliocene
Miocene
late
middle
early
Pleistocene
Plio.
e.
Plio. to Pleist.
Mio.
Pliocene to Pleistocene
l.
Silty clay/clayey silt
Diatomaceous ooze/ hemipelagic mud
Limestone/chalk/ nannofossil ooze
Calcareous clay
Prism sediments
Turbidite sediments
Hydrothermally altered sediments
Basement: basalt or gabbro
Décollement

Figure 3

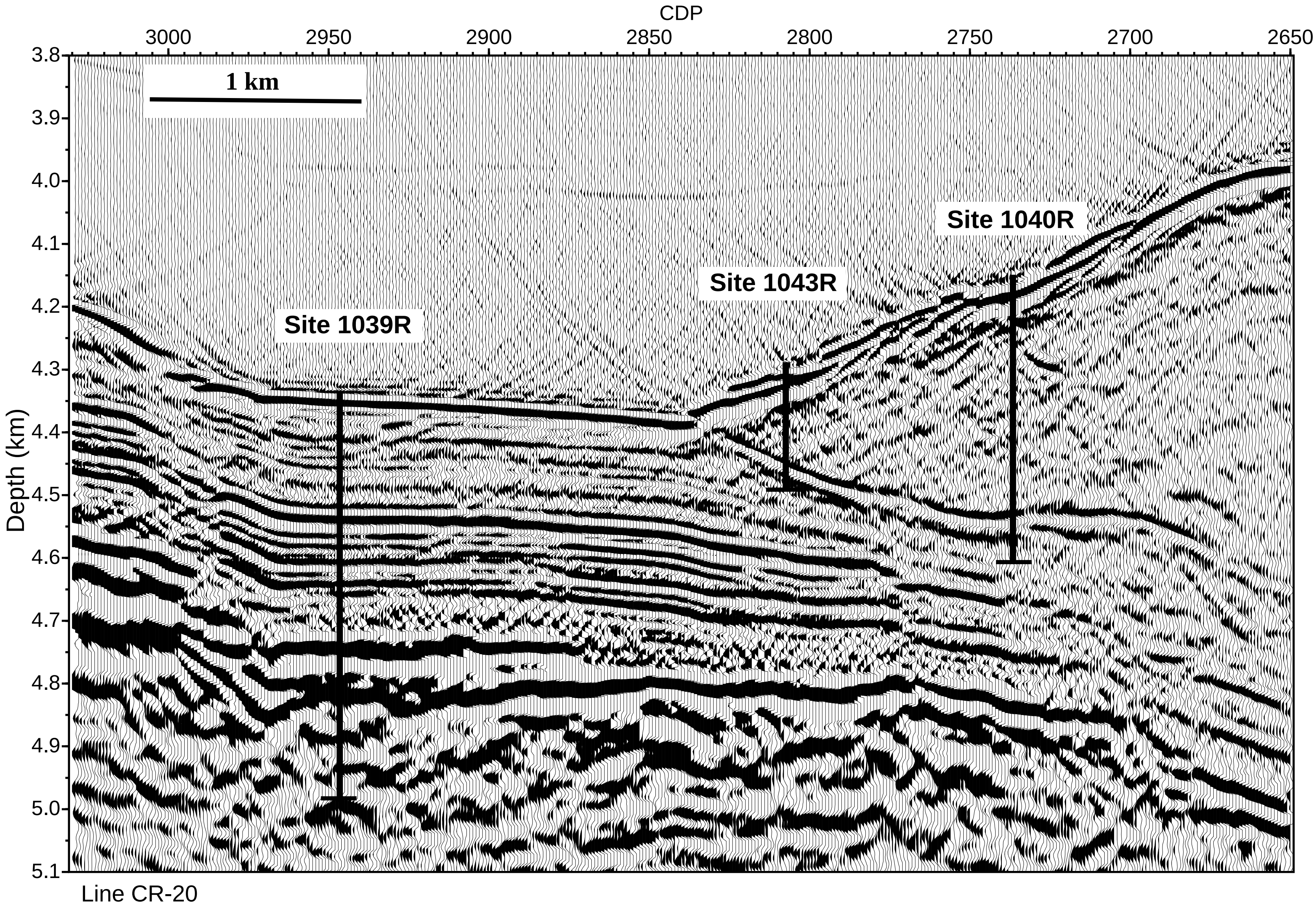
CDP
3000
2950
2900
2850
2800
2750
2700
2650
1 km
Site 1040R
Site 1043R
Site 1039R
Depth (km)
3.8
3.9
4.0
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5.0
5.1
Line CR-20

Figure 4A

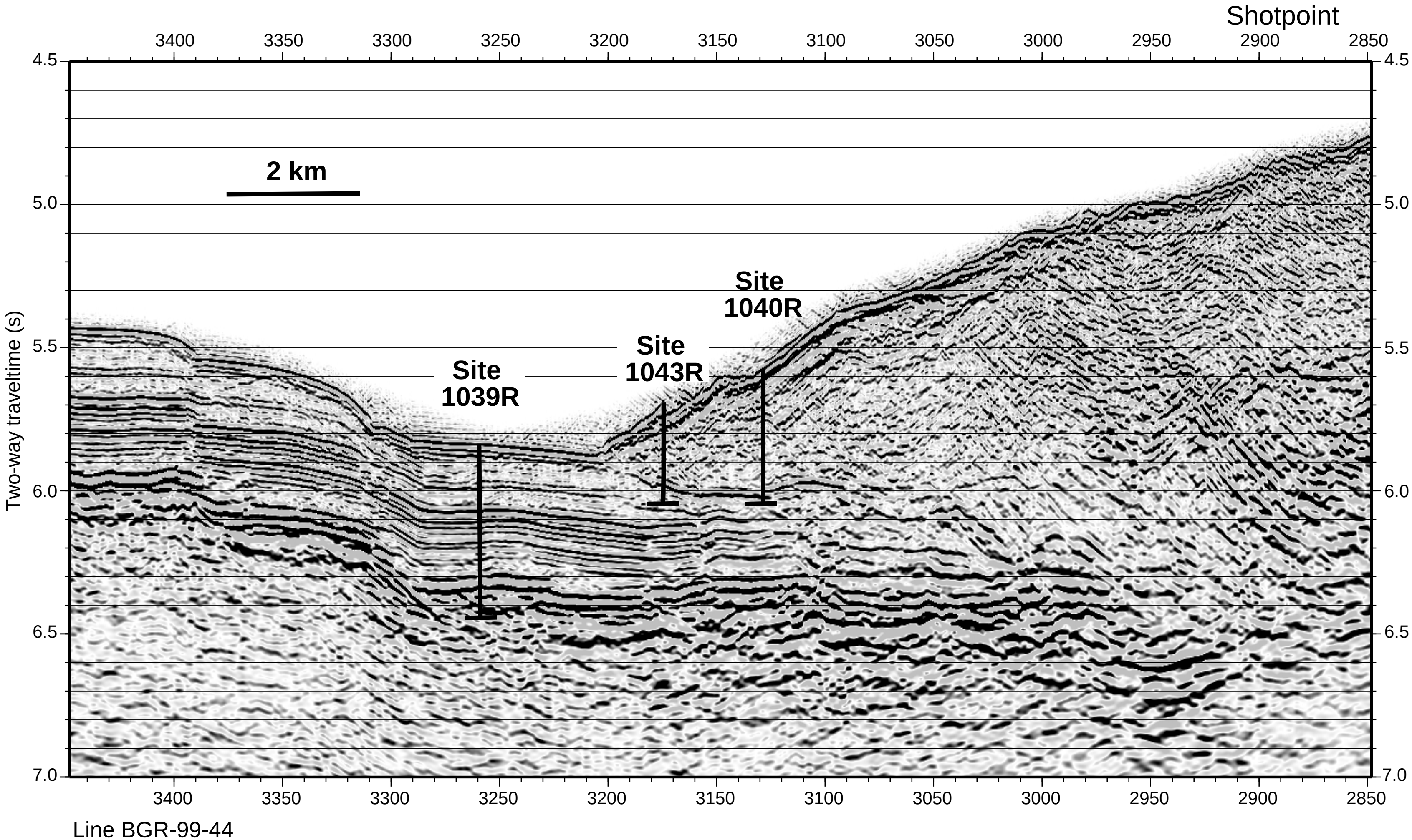
Shotpoint
3400
3350
3300
3250
3200
3150
3100
3050
3000
2950
2900
2850
4.5
5.0
5.5
6.0
6.5
7.0
Two-way traveltime (s)
2 km
Site 1040R
Site 1043R
Site 1039R
Line BGR-99-44

Figure 4B

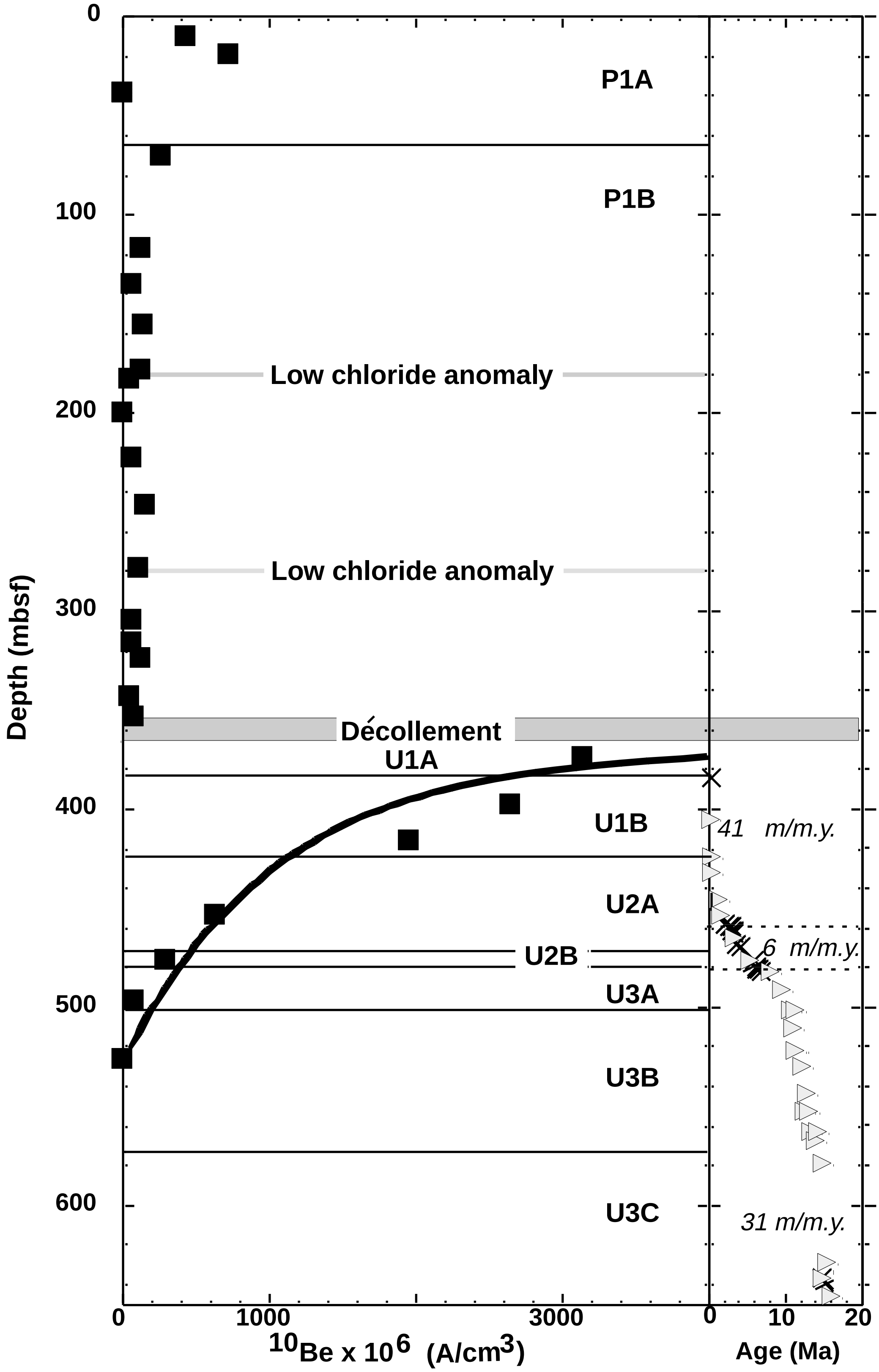
0
100
200
300
400
500
600
Depth (mbsf)
P1A
P1B
Low chloride anomaly
Low chloride anomaly
Décollement
U1A
U1B
U2A
U2B
U3A
U3B
U3C
41 m/m.y.
6 m/m.y.
31 m/m.y.
0
1000
3000
10Be x 10 6 (A/cm3)
0
10
20
Age (Ma)

Figure 5

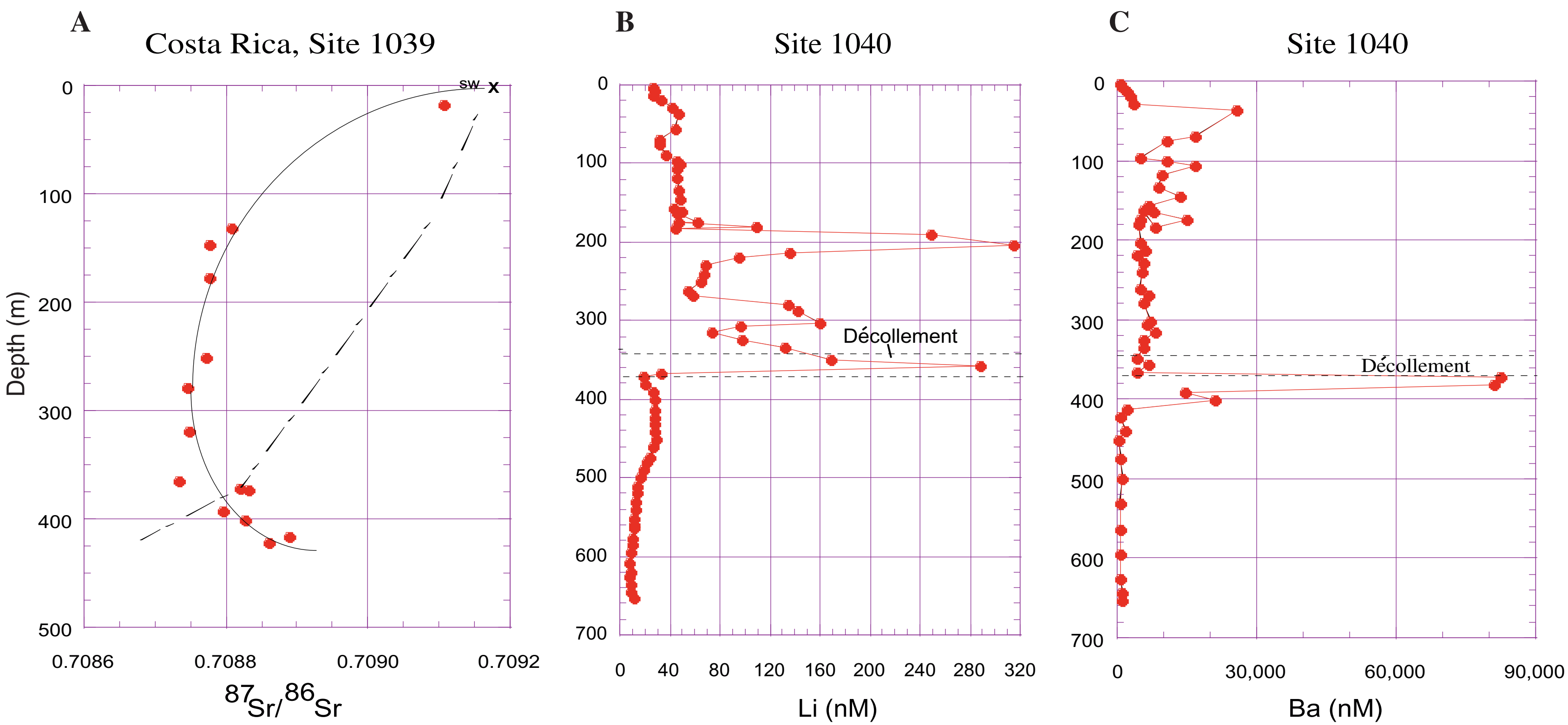
A
Costa Rica, Site 1039
Depth (m)
0
100
200
300
400
500
sw
x
0.7086
0.7088
0.7090
0.7092
87Sr/86Sr
B
Site 1040
Décollement
0
100
200
300
400
500
600
700
0
40
80
120
160
200
240
280
320
Li (nM)
C
Site 1040
Décollement
0
100
200
300
400
500
600
700
0
30,000
60,000
90,000
Ba (nM)

Figure 6

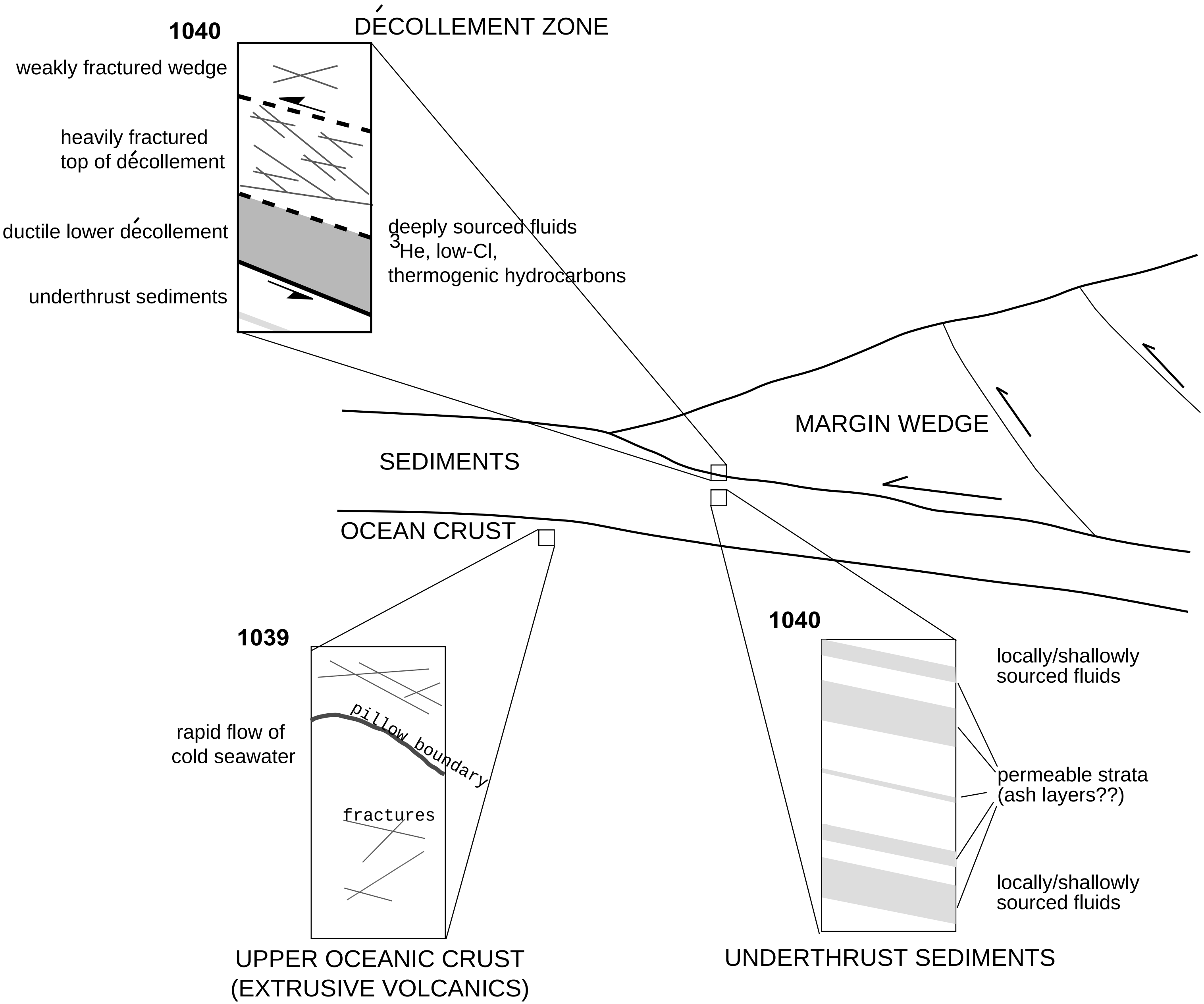
1040
DÉCOLLEMENT ZONE
weakly fractured wedge
heavily fractured
top of décollement
ductile lower décollement
underthrust sediments
deeply sourced fluids
^{3}He, low-Cl,
thermogenic hydrocarbons
MARGIN WEDGE
SEDIMENTS
OCEAN CRUST
1039
rapid flow of
cold seawater
pillow boundary
fractures
UPPER OCEANIC CRUST
(EXTRUSIVE VOLCANICS)
1040
locally/shallowly
sourced fluids
permeable strata
(ash layers??)
locally/shallowly
sourced fluids
UNDERTHRUST SEDIMENTS

Figure 7

Leg 205 Primary Site 1039R
Basement Osmo-sampler Installation Configuration

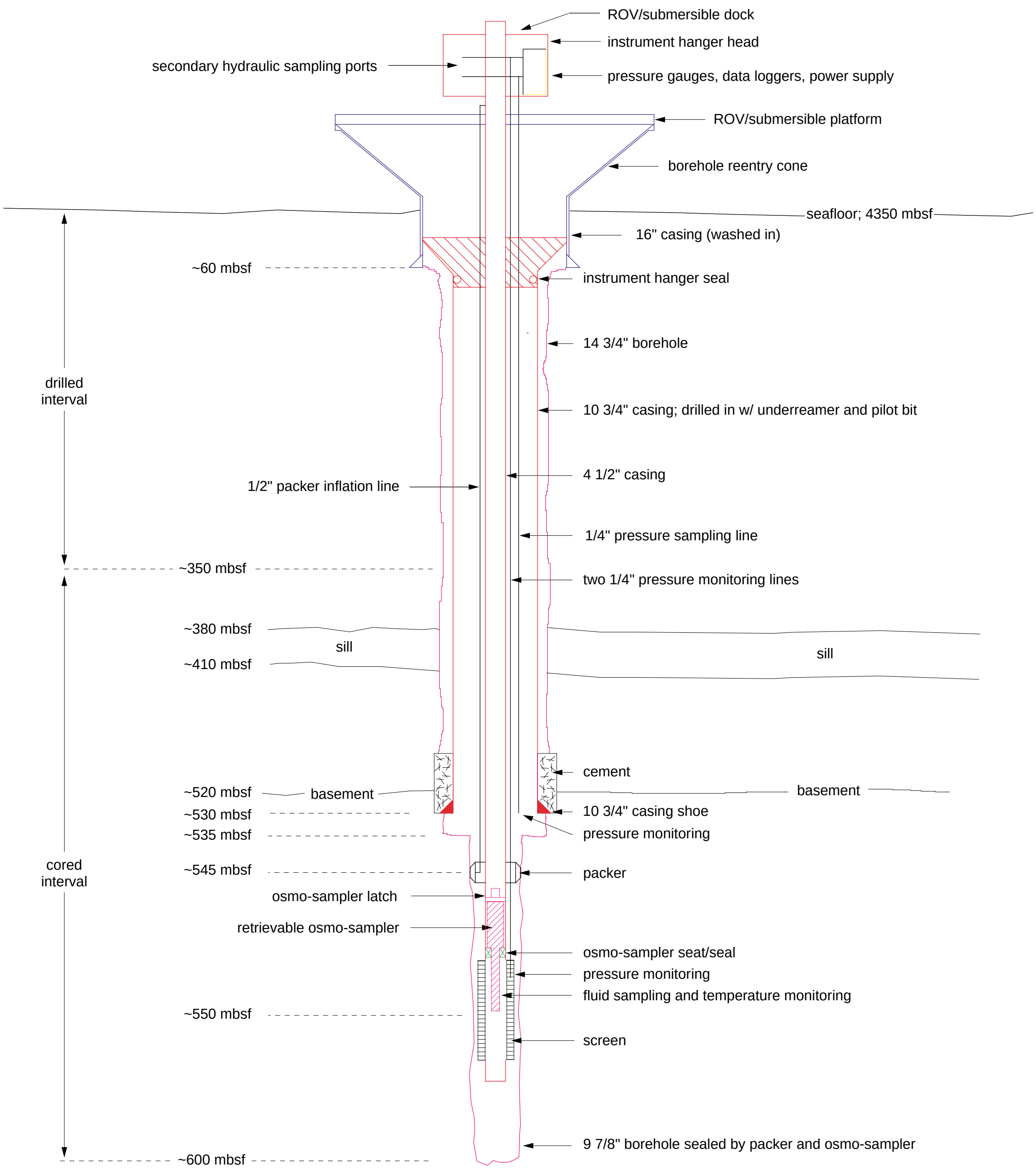

Figure 8A

Leg 205 Primary Site 1040R
Underthrust Osmo-sampler Installation Configuration

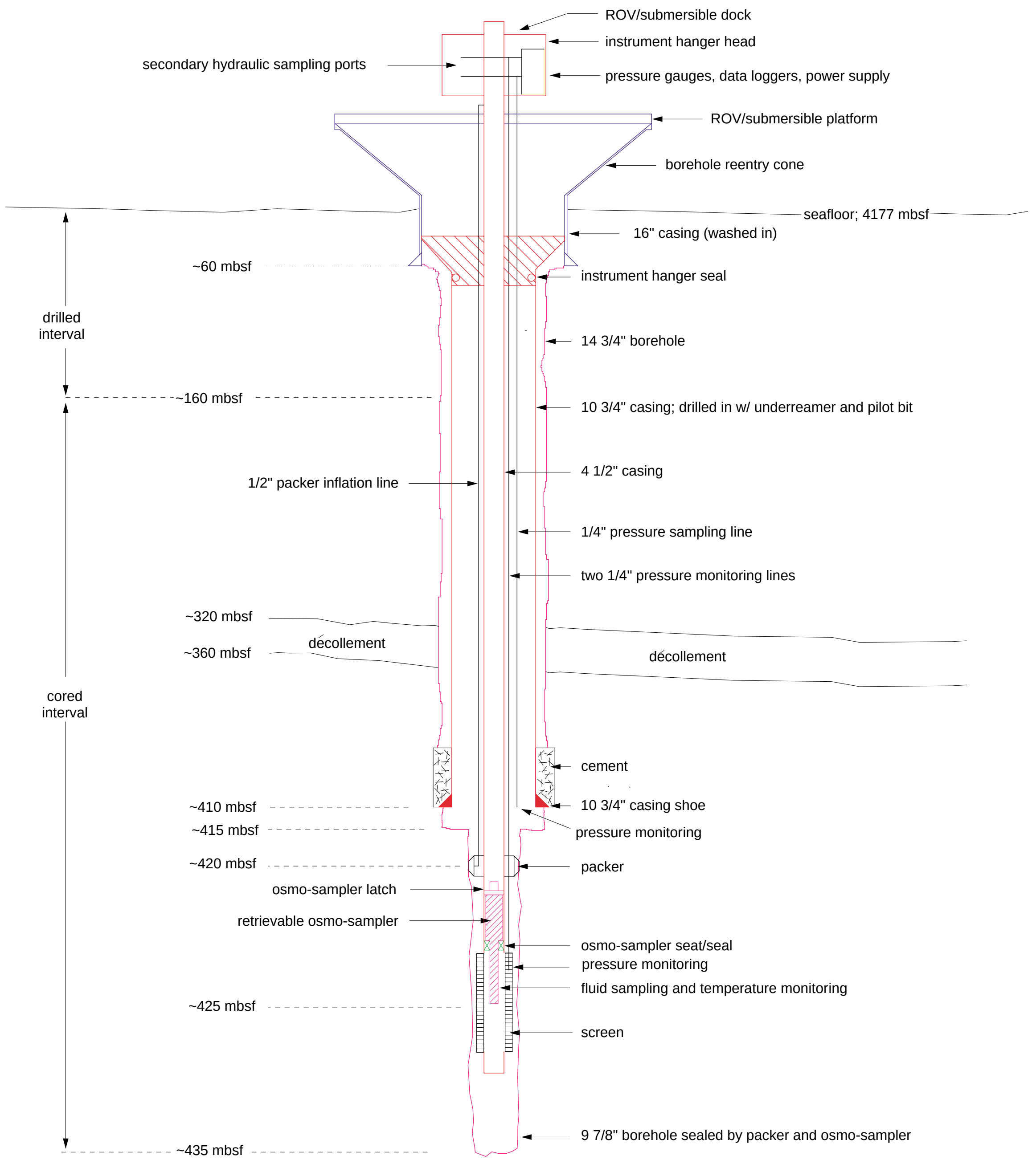

Figure 8B

Leg 205 Primary Site 1040R
Décollement Osmo-sampler Installation Configuration

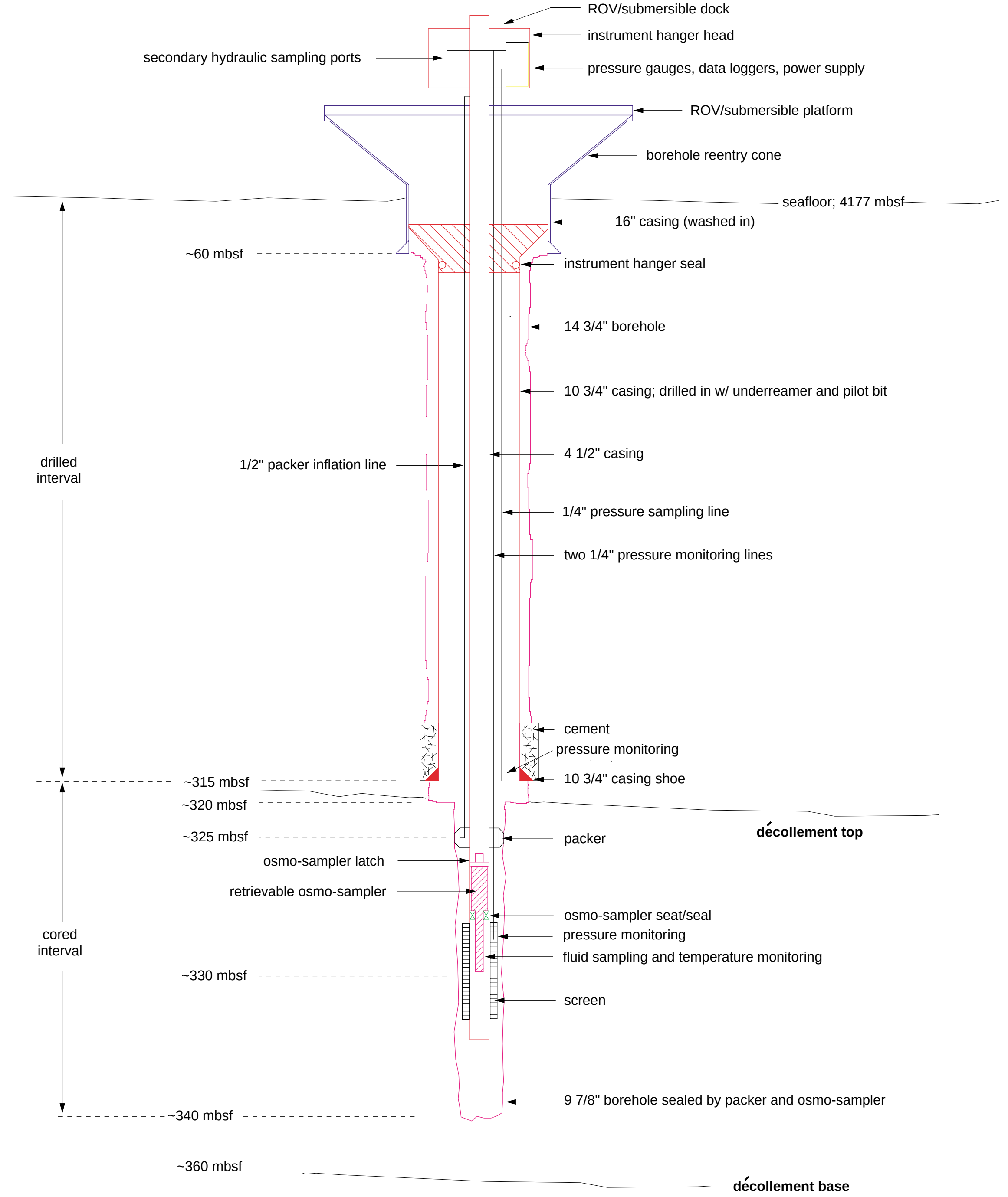

Figure 8C

Table 1. Operations plan and time estimate for Leg 205 primary sites.

Site No.	Location Lat./Long.	Water Depth	Operations Description	Transit (days)	On-Site (days)
San Diego, USA	32.45°N 117.10°W		Transit 2422 nmi San Diego to Site 1039R	9.6	
1039R Basement	9.64°N 86.20°W	4352 m	Set reentry cone w/ 60 m 16" casing		16.5
			Drill 60 - 340 mbsf, RCB core 340 - 600 mbsf (80 m basement)		
			Set and cement 10-3/4" casing to 530 mbsf		
			Install osmo-sampler screen @ 550 mbsf w/ packer @ 545 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
Transit			Transit 2.8 nmi Site 1039R to Site 1040R	0.1	
1040R-A Underthrust	9.66°N 86.18°W	4177 m	Set reentry cone w/ 60 m 16" casing		11.6
			Drill 0 to 180 mbsf, RCB 180-435 mbsf		
			Set 10-3/4" casing to 410 mbsf		
			Install osmo-sampler screen @ 425 mbsf w/ packer @ 420 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
1040R-B Decollement	9.66°N 86.18°W	4177 m	Set reentry cone w/ 60 m 16" casing		7.2
			Set and cement 10-3/4" casing to 315 mbsf		
			Install osmo-sampler screen @ 330 mbsf w/ packer @ 325 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
1040R-C Decollement	9.66°N 86.18°W	4177 m	Set reentry cone w/ 60 m 16" casing		7.2
			Set and cement 10-3/4" casing to 315 mbsf		
			Install osmo-sampler screen @ 330 mbsf w/ packer @ 325 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
Balboa, Panama	8.57°N 79.33°W		Transit 632 nmi Site 1040R to Balboa, Panama	2.8	
			Subtotal:	**12.5**	**42.5**
			ESTIMATED OPERATING DAYS TOTAL:	**55.0**	

Table 2. Leg 205 Site Time Estimate for Alternate Sites

Site No.	Location Lat./Long.	Water Depth	Operations Description	Transit (days)	On-Site (days)
1040R-D Fluid Conduit	9.66°N 86.18°W	4177 m	Set reentry cone w/ 60 m 16" casing		7.1
			Set 10-3/4" casing to 185 mbsf		
			Install osmo-sampler screen @ 200 mbsf w/ packer @ 195 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
1043R	9.65°N 86.19°W	4313 m	Set reentry cone w/ 60 m 16" casing		7.1
			Set 10-3/4" casing to 185 mbsf		
			Install osmo-sampler screen @ 200 mbsf w/ packer @ 195 mbsf		
			Install osmo-sampler		
			Deploy ROV/submersible platform		
			Alternate Site Transit and On-Site Time Totals:	**0.0**	**14.2**

ALTERNATE SITE OPERATIONAL DAYS TOTAL:	**14.2**

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