Integrated Ocean Drilling Program
Expeditions 309 and 312 Scientific Prospectus

Superfast Spreading Rate Crust 2 and 3

A complete in situ section of upper oceanic crust formed at a superfast spreading rate

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DISCLAIMER

This IODP Scientific Prospectus is based on precruise Science Advisory Structure panel discussions and scientific input from the designated Co-Chief Scientists on behalf of the drilling proponents. During the course of the cruise, actual site operations may indicate to the Co-Chief Scientists and the Operations Superintendent 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 science deliverables outlined in the plan presented here are contingent upon the approval of the IODP-USIO Science Services, TAMU, Deputy Director of Science Services in consultation with IODP-MI.

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ABSTRACT

Integrated Ocean Drilling Program (IODP) Expeditions 309 and 312 will complete drilling of a continuous section through volcanic basement and the underlying sheeted dike complex and into the uppermost plutonic rocks at Ocean Drilling Program (ODP) Site 1256. The crust at this site formed at a superfast (>200 mm/y) spreading rate ~15 m.y. ago at the East Pacific Rise. In preparation for deep drilling, during ODP Leg 206 a reentry cone and 16 inch casing were installed and cemented into basement in Hole 1256D and coring was completed to 500 meters subbasement (msb) within the volcanic section.

The relationship between ocean ridge spreading rate and depth to axial low-velocity zones, interpreted to be subaxial melt lenses, predicts that the dike–gabbro transition should occur at 900–1300 msb at Site 1256. We estimate reaching a depth of 1450 msb during Expeditions 309 and 312 and so should penetrate gabbroic rocks, allowing determination of the lithology and structure of the upper oceanic crust and definition of the thickness of the volcanic and sheeted dike sections. Recovered cores will enable investigations of magmatic processes within the axial melt lens and determination of whether upper gabbros are cumulates complementary to dikes and lavas or coarse-grained equivalents of extrusive rocks. Mineral studies will enable determination of cooling rates within the melt lens, and structural studies will examine the roles of faulting and fracturing in crustal accretion and hydrothermal circulation.

We will correlate remotely measured geophysical parameters of the crust with basic geological observations. Core observations and downhole logging will allow calibration of seismic velocities with lithology and enable determination of the relationships between seismic transitions (e.g., the Layer 2/3 boundary) and lithology and metamorphism. Magnetic measurements will establish the contribution of different lithologies and alteration to marine magnetic anomalies. We will investigate interactions between magmatic processes, rock type, and hydrothermal water-rock interaction, including testing the alteration "stratigraphy" within extrusive volcanic rocks and sheeted dikes established in Hole 504B, as well as in the underlying gabbroic rocks. Core studies will determine the nature of the deep subsurface reaction and shallower mixing zones, establish geochemical budgets for the Site 1256 crust, and examine the depth extent of the subsurface biosphere in igneous basement.

Initial logging during Expedition 309 will sample borehole fluid and determine temperature and hole conditions. Full logging suites collected at or near the end of Expe-

dition 309 and at the end of Expedition 312 will relate recovered material to the crust and core and borehole geophysical measurements to remote surveys of crustal properties.

SCHEDULE FOR EXPEDITIONS 309 AND 312

Expeditions 309 and 312 are based on Integrated Ocean Drilling Program (IODP) drilling proposal number 522-Full3 (available at **iodp.tamu.edu/scienceops/expeditions/exp309.html**). Following ranking by the IODP Scientific Advisory Structure, the expeditions were scheduled by the IODP Operations Committee for the research vessel *JOIDES Resolution,* operating under contract with the U.S. Implementing Organization (USIO). Expedition 309 is currently scheduled to begin in Balboa, Panama, on 10 July 2005 and to end in Balboa on 28 August 2005. A total of 38 days will be available for the drilling, coring, and downhole measurements described in this report. Expedition 312 is currently scheduled to begin in Balboa, Panama, on 14 November 2005 and to end in Balboa on 28 December 2005. A total of 35 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 on the *JOIDES Resolution* can be found at **iodp.tamu.edu/publicinfo/drillship.html.**

INTRODUCTION

Accretion of oceanic crust is a major means of heat loss from the Earth's interior and is a fundamental component of the plate tectonic processes responsible for formation and evolution of our planet's surface. Hydrothermal interactions at mid-ocean spreading centers and on ridge flanks influence the chemistry of the oceans and, through subduction, the composition of the upper mantle. Despite the role the ocean crust has played in the evolution of our planet, our sampling of in situ oceanic basement remains rudimentary. Samples of basalts, dikes, gabbros, and peridotites have been retrieved by dredging and shallow drill holes from most of the ocean basins, but the geological context of these samples is rarely well established. As such, the nature and variability of the composition and structure of the ocean crust away from transform faults and other tectonic windows remains poorly known.

Drilling a complete crustal section has always been a major goal of ocean drilling (Bascom, 1961; Shor, 1985), but this goal has been impeded by technical difficulties and the time investments required. The distribution of drill holes in intact oceanic crust of different ages and formed at different spreading rates is extremely sparse (Fig. **F1**). Hole 504B, on the southern flank of the Costa Rica Rift, remains the only hole to penetrate extrusive lavas and most of the way through the sheeted dike complex. The dike/gabbro boundary has never been drilled, and the nature of the plutonic rocks directly underlying the sheeted dike complex is not well established, despite this zone being perhaps the most influential in determining the mechanisms of crustal accretion and the geometry of magmatic and hydrothermal interactions. Importantly, there are few significant penetrations (>100 m) of crust generated at a fast or superfast spreading ridge and, before Leg 206, only one (Hole 1224F) in relatively young ocean crust (<50 Ma) formed at a fast spreading rate. Our poor sampling of ocean crust at different spreading rates and crustal ages and absence of information on crustal variability compromises our ability to extrapolate observations from specific sites to global descriptions of magmatic accretion processes and hydrothermal exchange in the ocean crust.

Oceanic crust formation and evolution is one of the primary themes for investigation in the Initial Science Plan for the Integrated Ocean Drilling Program (International Working Group, 2001) and other major science priority submissions (e.g., Conference on Multiple Platform Exploration of the Ocean [COMPLEX]: Pisias and Delaney, 1999; Ocean Drilling Program [ODP] Geochemistry Futures Workshop: Murray et al., 2002). These documents and others specifically related to the study of the oceanic lithosphere (Second Conference on Scientific Ocean Drilling [COSOD II]; ODP Long Range Plan, 1996; ODP–International Cooperation in Ridge-Crest Studies [InterRIDGE]–International Association of Volcanology and Chemistry of the Earth's Interior [IAVCEI] workshop; 4D-Architecture of the Ocean Crust Program Planning Group) reemphasize deep drilling to obtain complete sections of the ocean crust as a priority and note that the deep drilling capabilities of riserless technology have yet to be fully utilized. Offset drilling strategies, where deeper portions of the ocean crust are sampled by drilling in tectonic windows, have recently been high priorities for ocean drilling (COSOD II, 1987; ODP Long Range Plan, 1996). Drilling at several sites has provided a wealth of new data and understanding of gabbros and peridotites from the lower crust and upper mantle (e.g., Hess Deep: Gillis, Mével, Allan, et al., 1993; Kane Fracture Zone area [MARK]: Cannat, Karson, Miller, et al., 1995; Southwest Indian Ridge [SWIR]: Dick, Natland, Miller, et al., 1999; 14°–16°N Mid-Atlantic Ridge [MAR]: Kelemen, Kikawa, Miller, et al., 2004; Atlantis Massif: Expedition Scientific Party, 2005a, 2005b). However, serious problems still exist in drilling tectonized rocks with little sediment blanket or without erosional removal of fractured material, and it is also commonly difficult to relate drilled sections to regional geology. Composite sections are not substitutes for deep, in situ penetrations, and drilling deep holes to obtain complete upper crustal sections continues to be a primary challenge for scientific ocean drilling (Dick and Mevel, 1996; Murray et al., 2002).

Unfortunately, there are no on-land alternatives to drilling in the oceans. Although ophiolites, ancient slices of ocean crust now preserved on land, provided much of the early inspiration for ocean crust studies, the classic outcrops of Semail ophiolite (Oman) and Troodos massif (Cyprus) formed in suprasubduction zone settings and their different magma and volatile chemistries compromise their applicability to understanding processes in the major ocean basins. Macquarie Island (Varne et al., 2000), uplifted along the Australian/Pacific plate boundary ~1000 km south of New Zealand, may be the only outcrop of subaerially exposed ocean crust formed at a mid-ocean ridge, but the island is complexly faulted and is an environmentally sensitive United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage site from which drilling, even for scientific purposes, is prohibited.

IODP Expeditions 309 and 312 will deepen ODP Hole 1256D (Fig. **F2, F3**), which already extends 502 m into basement, to core through the sheeted dike complex and into plutonic rocks in a section of crust generated at a superfast spreading rate in the eastern Pacific to

- Provide the first sampling of a complete section of ocean crust from extrusive rocks, dikes, and into the gabbros;
- Confirm the nature of high-level axial magma chambers; and
- Define the relationship between magma chambers and their overlying lavas and the interactions between magmatic, hydrothermal, and tectonic processes.

SCIENTIFIC OBJECTIVES

1. Test the prediction, from the correlation of spreading rate with decreasing depth to the axial melt lens, that gabbros representing the crystallized melt lens will be encountered at 900–1300 m subbasement (msb) at Site 1256.

The transition from sheeted dikes to gabbros has never been drilled, and this remains an important objective in achieving a complete or even composite crustal section. The dike–gabbro transition and the uppermost plutonic rocks are assumed to be the frozen axial melt lens and the fossil thermal boundary layer between magma chambers and vigorous hydrothermal circulation. Detailed knowledge of the dike–gabbro transition zone is critical to discerning the mechanisms of crustal accretion. The textures and chemistries of the uppermost gabbros are presently unknown but are central to understanding crustal construction; to date we lack samples that link gabbroic rocks to the overlying lavas, leading to the following questions:

- What is the geological nature of the low-velocity zones imaged by multichannel seismic reflection studies at the axes of mid-ocean ridges?
- Are the upper gabbros cumulate rocks from which magmas were expelled to form the dikes and lavas that then subsided to form the lower crust, or are the uppermost gabbros coarse-grained chemical equivalents of the extrusive rocks frozen at the base of the sheeted dikes?
- Does most of the crustal accretion occur at deeper levels through the intrusion of multiple narrow sills?
- What are the cooling rates of magma chambers?

These questions can be answered through petrographic and geochemical (major and trace elements) studies of gabbros (e.g., Natland and Dick, 1996; Kelemen et al., 1997; Manning et al., 2000; MacLeod and Yaoancq, 2000; Coogan et al., 2002a, 2000b) and the overlying lavas and their mineral constituents.

2. Determine the lithology and structure of the upper oceanic crust for the superfast-spreading

end-member.

Some basic observations regarding the architecture of ocean crust, including the lithology, geochemistry, and thicknesses of the volcanic and sheeted dike sections and how these vary with spreading rate or tectonic setting, are not well known. Karson (2002) provides estimates of the thicknesses of lavas and sheeted dikes from crust generated at fast and intermediate spreading rates (600–900 m lavas and 300–1000 m dikes at Hess Deep; 500–1300 m lavas and 500 to >1000 m dikes in Hole 504B and Blanco Fracture Zone), but these are based mainly on tectonized exposures, where tectonic complexities increase uncertainties in the estimates. Results of Expeditions 309 and 312 will provide the thicknesses of these upper crustal units at Site 1256.

Studies of tectonic exposures of oceanic crust suggest that faulting and distributed zones of fracturing are common within sheeted dike complexes in crust formed at fast and intermediate spreading rates (Karson, 2002). In contrast, sheeted dike complexes in the Semail ophiolite in Oman exhibit little of such faulting and distributed fracturing (Umino et al., 2003). Drilling the sheeted dike complex at Site 1256 will enable evaluation of whether such faulting and fracturing in tectonic exposures are representative of oceanic crust or whether they may be related to their tectonic setting.

Most dikes in sheeted dike complexes in tectonic exposures of crust generated at intermediate and fast spreading rates and in Hole 504B in intermediate-rate crust generally dip away from the spreading axis, suggesting tectonic rotation of crustal blocks (Karson, 2002). Do such rotations occur in crust generated at superfast spreading rates, and are they similar, or is the crust less tectonically disrupted? A single drill hole may not conclusively answer this question but should provide important constraint.

3. *Correlate and calibrate remote geophysical seismic and magnetic imaging of the structure of the crust with basic geological observations.*

Ground-truthing regional geophysical techniques such as seismics and magnetic measurements is a key goal of the IODP Initial Science Plan and related documents (e.g., COMPLEX). A fundamental question we will address in this experiment is how velocity changes within seismic Layer 2 and the Layer 2–Layer 3 transition relate to physical, lithological, structural, and alteration variations in the volcanic rocks, dikes, and gabbros. At Site 504 in crust generated at an intermediate-rate spreading ridge, the Layer 2–Layer 3 transition lies within the 1 km thick sheeted dike complex and coincides with a metamorphic change (Detrick et al., 1994; Alt et al., 1996), but is this representative of ocean crust and of crust generated at different spreading rates? Is the depth to gabbros shallower in crust generated at a superfast spreading rate, as predicted, and what are the relative thicknesses of volcanic and dike sections compared with crust constructed at slow or intermediate spreading rates?

Marine magnetic anomalies are one of the key observations that led to the development of plate tectonic theory, through recognition that the ocean crust records the changing polarity of the Earth's magnetic field through time (Vine and Matthews, 1963). It is generally assumed that micrometer-sized grains of titanomagnetite within the erupted basalts are the principal recorders of marine magnetic anomalies, but recent studies of tectonically exhumed lower crustal rocks and serpentinized upper mantle indicate that these deeper rocks may also be a significant source of the magnetic stripes. Coring a complete section through the sheeted dike complex allows evaluation of the contribution of these rocks to marine magnetic anomalies. Whether these deeper rocks have a significant influence on the magnetic field in undisrupted crust is unknown, as is the extent of secondary magnetite growth in gabbros and mantle assemblages away from transform faults. Sampling the plutonic layers of the crust will test the Vine-Matthews hypothesis by characterizing the magnetic properties of gabbros through drilling normal ocean crust on a well-defined magnetic stripe, away from transform faults.

4. *Investigate the interactions between magmatic and alteration processes, including the relationships between extrusive volcanic rocks, feeder sheeted dikes, and underlying gabbroic rocks.*

Little information presently exists on the heterogeneity of hydrothermal alteration in the upper crust or the variability of associated thermal, fluid, and chemical fluxes. How these phenomena vary at similar and different spreading rates is unknown. Metamorphic assemblages and analyses of secondary minerals in material recovered by deep drilling can provide limits on the amount of heat removed by hydrothermal systems and place important constraints on the geometry of magmatic accretion and the thermal history of both the upper and lower crust (e.g., Manning et al., 2000; MacLeod and Yaoancq, 2000; Coogan et al., 2002a, 2000b). Fluid flow paths, the extent of alteration, and the nature of deep subsurface reaction and shallower mixing zones are all critical components of our understanding of hydrothermal processes that can only be tackled by drilling. These problems can be addressed by examining the "stratigraphy" and relative chronology of alteration within the extrusive lavas and dikes, by determining whether disseminated sulfide mineralization resulting from fluid mixing and a large step in thermal conditions is present at the volcanic–dike transition (as in Hole 504B and many ophiolites), and by evaluating the grade and intensity of alteration in the lower dikes and upper gabbros. The lowermost dikes and upper gabbros have been identified as the conductive boundary layer between the magma chambers and the axial high-temperature hydrothermal systems, as well as the subsurface reaction zone where downwelling fluids acquire black-smoker chemistries (Alt, 1995; Alt et al., 1996; Vanko and Laverne, 1998; Gillis et al., 2001). However, extensive regions of this style of alteration or zones of focused discharge are poorly known, and information from ophiolites may not be applicable to in situ ocean crust (Richardson et al., 1987; Schiffman and Smith, 1988; Bickle and Teagle, 1992; Gillis and Roberts, 1999). Drilling beyond the boundary between the lower dikes and upper gabbros will allow tracing recharge fluid compositions, estimating hydrothermal fluid fluxes (e.g., Teagle et al., 1998, 2003), and integrating the thermal requirements of hydrothermal alteration in sheeted dikes and underlying gabbros with the magmatic processes in the melt lens. Detailed logging of cores combined with geochemical analyses will enable determination of geochemical budgets for hydrothermal alteration (e.g., Alt et al., 1996; Alt and Teagle, 2000; Bach et al., 2003). Is there a balance between the effects of low-temperature alteration of lavas versus high-temperature hydrothermal alteration of dikes and gabbros? This is a critical check on global budgets for many elements (Mg, K, ^{87}Sr, U, and ^{18}O) presently estimated from vent fluid chemistries, riverine inputs, and thermal models (e.g., review of Elderfield and Schultz, 1996).

Microbial alteration of volcanic glass decreases with basement depth at other sites (Furnes and Staudigel, 1999), but the temperature and depth limits to subbasement microbiological activity can be investigated by deep sampling and study of glass alteration or other geochemical indicators (e.g., Blake et al., 2001; Alt et al., 2003).

DRILLING STRATEGY

The operational strategy for Expeditions 309 and 312 is to core as deep as possible in Hole 1256D, including complete borehole coverage with conventional wireline logging tools (Table **T1**). Operational time for these expeditions includes 38 days on site for Expedition 309 and 35 days on site for Expedition 312. Using pipe-trip times appropriate for the water and hole depths and assuming 50 h of rotation on each of 12–15 CC-9 rotary core barrel (RCB) coring bits (determined to be the best available for coring at Site 1256 during Leg 206), we expect to achieve a minimum depth of at least 1450 m into basement (1700 meters below seafloor [mbsf]). A penetration rate of 1.5 m/h has been assumed in this estimate, which was the average rate of penetration toward the end of drilling during Leg 206 and is similar to rates achieved during operations in sheeted dikes in Hole 504B during Legs 140 and 148 (Dick, Erzinger, Stokking, et al., 1992; Alt, Kinoshita, Stokking, et al., 1993).

For a spreading rate of >200 mm/y, the low-velocity zone interpreted as a melt lens is predicted to occur at a depth between 725 and 1000 m at the ridge axis (Fig. **F4**). The steep magnetic inclinations of the uppermost lavas sampled in Holes 1256C and 1256D (Wilson, Teagle, Acton, et al., 2003) as well as the ~100 m thickness of the ponded lava flow (Units 1256C-18 and 1256D-1) suggest that the magma flowed or was erupted a considerable distance off axis (~5 km). Assuming that there is at least 100–200 m of additional lavas that flowed relatively short distances from the axis (1–2 km), we predict that gabbros representing the frozen axial low-velocity zone should occur at ~925–1300 msb (1175–1550 mbsf), providing 150–525 m of gabbro penetration if the proposed drilling scenario is achieved (Fig. **F5**).

Using the lowermost heat flow measurement taken in Hole 1256C (109 mW/m^2), the temperature at the sediment/basement boundary (35°C), and appropriate thermal conductivities for lavas, dikes, and gabbroic rocks, we predict that the ambient temperature at 1700 mbsf in Hole 1256D should be ~100°–140°C, significantly cooler than that encountered in Hole 504B (~170°C) at these depths.

Our operations schedule includes time for preliminary logging of Hole 1256D, which will require a dedicated round trip of the drill string, so that an equilibrium temperature profile and water sample can be recovered before the thermal structure of the crust is perturbed by drilling operations. We also expect to evaluate the diameter and eccentricity of the borehole with the triple combination (triple combo) tool string. In the unexpected case of significant fill and/or large changes in hole diameter, additional passes with Formation MicroScanner (FMS) or Ultrasonic Borehole Imager (UBI) may be made to evaluate the need for casing. A full suite of wireline logging tools will be deployed after the completion of drilling operations, following an order of operations similar to that used during Leg 206 (see **"Triple Combination Tool String," "Formation MicroScanner–Dipole Sonic Imager Tool String," "Ultrasonic Borehole Imager,"** and **"Three-Component Well Seismic Tool"** in "**Logging Strategy**"). We also expect to run a three-component borehole magnetometer. We have requested funding to deploy the DMT Digital Color 360° CoreScan system or similar to digitally record the outer surface of all cores. Core-logging integration will be enhanced through the use of this system, as used during Leg 206.

Contingency Plans Should Drilling Difficulties Arise in Hole 1256D

Although hole developments and drilling in Hole 1256D during Leg 206 were exhaustive and prepared the site for the best possible chance of successful deep drilling down to the gabbros, drilling upper oceanic basement will always be technically challenging and risk of hole collapse or drill string failure will always exist. As such, it is prudent that a range of contingency options be considered and approved precruise so that the best decisions can be made should the need arise.

The underlying philosophy for this experiment to drill a complete section of in situ upper oceanic crust was to construct a borehole engineered specifically for deep drilling. In Hole 1256D, the borehole infrastructure includes a large reentry cone supported by 95 m of 20 inch casing and 270 m of 16 inch casing that penetrates completely through the sedimentary overburden and is cemented ~20 m into the basement. This arrangement allows two further casing strings ($13^{3}/_{8}$ inch and then $10^{3}/_{4}$ inch) to be deployed in the hole should the need arise to isolate and armor a section of basement. Our drilling strategy and contingency plans must protect the integrity of Hole 1256D, in which there has already been significant investment, as well as utilize the engineering opportunities allowed by the ocean bottom structures already in place.

Potential failings that may occur during Expeditions 309 and 312 fall into two broad categories: (1) failure of the drill string, requiring fishing operations, and (2) collapse and instability of the borehole itself. Drill string failures may be directly linked to borehole wall collapses. To mitigate against drill string failures we will adopt a conservative drilling strategy, with consistent core recovery taking priority over rapid penetration. Where necessary, half-cores (4.5 m) will be taken if core recovery becomes very low, so at least some rocks will be recovered from all intervals. The drilling operations team will ensure that Expeditions 309 and 312 will sail with the best possible arsenal of fishing tools (fishing jars, intensifiers), so should drill string or other equipment be lost in Hole 1256D we will have available all potentially useful tools to recover the lost equipment or mill it out.

Borehole failures are potentially more difficult to tackle. Casing a section of borehole a significant distance into Hole 1256D will require a very large expenditure of time and equipment. Deployment of the next-sized casing string ($13^{3}/_{8}$ inch) will require the hole to be reamed to an internal diameter of 18.5 inches before casing can be inserted. Table **T2** shows an estimation of the time required to open Hole 1256D to case a blockage at ~500 msb. Such an operation would take ~34 days, similar to the number of operational days on site for Expedition 309. Although installation of a smaller-diameter casing string ($10^3/_4$ inch) would require less milling and would be less technically difficult, such an approach would not allow further casing strings to be inserted into Hole 1256D and would make redundant the difficult engineering operations required to cement 16 inch casing into basement during Leg 206.

It should be noted that a deep basement casing operation has never been attempted in scientific ocean drilling, and the best reaming strategies and tools remain unknown. As such, we will adopt one of the following strategies should a borehole breach occur that requires a significant casing string to be installed in Hole 1256D.

1. To prepare for opening and casing Hole 1256D we will test hole opening strategies and tools including the deployment of 14.5 × 18.5 inch bicenter reamers coupled to $9^7/_8$ inch wobble bits and other potential tools to test their effectiveness and determine progress rates so that the best reaming and casing strategy can be developed ashore for future operations at the site.
2. If Hole 1256D suffers a catastrophic collapse or unrecoverable equipment failure and must be abandoned, we will use the time available to start a new deep hole close to Hole 1256D, including installation of 16 inch casing to basement. This operation should take ~8 days (Table **T2**). All equipment required for such an operation will be aboard the *JOIDES Resolution.* We will then drill ahead until the end of the cruise.
3. If Hole 1256D requires casing, following tests of reaming equipment (number 1, above), there are a number of other operations which could be conducted that would yield significant scientific return. These include the following:
   - Drilling a number of single-bit or free-fall funnel multi-bit holes in the environs of Hole 1256D to establish regional variation in upper crustal processes, lithologic structure, and seawater interactions would provide important information that is of high priority in the IODP Initial Science Plan. Determining the extent of the massive lava flow encountered in Holes 1256C and 1256D would constrain the size of off-axis eruptions. Drilling further afield in the GUATB-03 survey region would allow investigation of the significant variations in upper crustal velocities that were recognized across the survey region. The causes of these seismic velocity variations could be verified with a number of shallow holes combined with logging, providing important new knowledge on the range

of crustal architectures present in upper oceanic basement formed at fast spreading rates. Specific sites shown in Figure **F6** were selected from the pre-Leg 206 site survey cruise (Wilson et al., 2003) where crossing geophysical lines are available. Both of these sites were approved by the Site Survey Panel (SSP) and the Pollution Prevention Safety Panel (PPSP) as alternate sites for Leg 206. Slow seismic velocities in the southwest of the grid coincide with better-defined abyssal hill fabric and possibly more porous or rubbly material compared to Site 1256. As we anticipate drilling only shallow holes (200–300 msb), deep thrust structures imaged on some lines will not be encountered. As the sediment overburden in this region has been thoroughly characterized and shown to be regionally uniform by drilling at Sites 1256, 844, and 845, we request that we be allowed to wash through most of the sediment pile and initiate coring just above basement. All holes >100 m will be logged with a full suite of wireline tools to return the maximum information on the crustal architecture.

- Logging Hole 504B (1°13.6′ N, 83°43.8′ W). Hole 504B is presently the only crustal borehole to penetrate an entire section of lavas and sampled ~1 km of sheeted dikes. Because of tool failure during Leg 148, an FMS log of the entire hole was not achieved and the UBI was never deployed at that site. Because of its unique penetration, Hole 504B has been regarded as the oceanic crust reference site for more than a decade, but the absence of continuous imaging of the borehole walls and poor core recovery makes understanding the architecture of the oceanic basement at that site difficult and brings geochemical exchange budgets calculated from the distribution of the recovered cores into question. Transit to Hole 504B is ~2.5 days, and a full suite of logging operations would take ~5 days. Logging this site would provide important information critical to many key objectives regarding the architecture of the oceanic crust and chemical exchange between seawater and oceanic basement, highlighted in the initial science plan.
- Deepening Hole 896A (1°13.0′ N, 83°43.4′ W). Hole 896A was drilled during Leg 148 (Shipboard Scientific Party, 1993) following termination of operations in Hole 504B. The hole is sited on a basement high, ~1 km southeast of Hole 504B, where heat flow and pore water studies indicate ongoing upwelling of basement fluids. The hole was drilled to investigate local-scale heterogeneity of the ocean crust around Site 504 and the effects of basement topography on the intensity of hydrothermal alteration. Three specific objectives were addressed in Hole 896A during Leg 148: (1) to examine the local variability in volcanic stratigraphy, areal extent of lava flows, and horizontal and vertical variations in igneous geochemistry; (2) to examine the effects of off-axis hydrothermal activity on the basement

relating the composition of upwelling fluids in a high heat flow area to the alteration of the basement; and (3) to drill the second of a pair of deep basement holes from which future geophysical experiments between the paired holes can be conducted. Hole 896A is fitted with a reentry cone and 191 m of $11^{3}/_{4}$ inch casing. Basement was first encountered at 179 mbsf, and the hole was cored from 195.1 to 469 mbsf, 290 m into basement (Alt, Kinoshita, Stokking, et al., 1993). Deepening Hole 896A will provide important information on the variation of crustal structure in the vicinity of Hole 504B. The cores recovered so far have all incurred oxidative seawater alteration, but from Hole 504B one would predict that the transition to more reducing conditions occurs only a few tens of meters below the current depth of the hole. However, the depth of exchange with oxidative seawater may be dependent upon other hitherto unconstrained criteria, such as basement topography, volcanic stratigraphy, or sediment thickness. Knowledge of the variation of the penetration of oxidative seawater would be gained by deepening this hole, with important implications for refining geochemical budgets.

LOGGING STRATEGY

Downhole logging will be an important complement to coring operations during Expeditions 309 and 312 and will greatly assist in the attainment of the scientific objectives by providing continuous, in situ geophysical measurements on the drilled basalts, dikes, and gabbros. The logging program will refine the volcanic stratigraphy, eruptive morphology, and variations in seawater-basalt alteration as a function of depth as well as allow direct correlation of wireline measurements with discrete laboratory measurements on recovered core (e.g., Fig. **F7**). In addition, downhole measurements will be used in conjunction with core images from the DMT Core Scanner to reorient veins, fractures, and other features back into the geographic reference frame. Core recovery during drilling of igneous basement is often incomplete and biased, with weaker rock types preferentially lost. In contrast, wireline logging provides continuous data across all intervals including those with low recovery.

Five logging tool strings will be deployed in Hole 1256D during Expeditions 309 and 312, and the characteristics of these five tool strings are briefly described below. We anticipate that we will log Hole 1256D toward the end of Expedition 309 once significant penetration has been achieved, and logging will be the final act on site during Expedition 312. In addition, we have set aside time in the operations schedule for preliminary logging of Hole 1256D during Expedition 309, enabling an equilibrium temperature profile to be measured using the Water Sampling Temperature Probe (WSTP) and a deep basement water sample to be taken. The borehole will also be checked for breakouts and variations in hole diameter using the triple combo tool string.

Triple Combination Tool String

The triple combo tool string consists of five probes:

- The Accelerator Porosity Sonde (APS) uses an electronic neutron source to measure the porosity of the formation.
- The Hostile Environment Litho-Density Sonde (HLDS) measures bulk density.
- The Hostile Environment Gamma Ray Sonde (HNGS) measures natural radioactivity of the formation and provides indications of the Th, U, and K concentrations. These measurements can then be integrated with analytical studies to determine downhole geochemical variations in alteration.
- The Dual Laterolog (DLL) tool will be used to measure rock resistivity at two invasion depths.
- The Lamont-Doherty Earth Observatory (LDEO) Temperature/Acceleration/Pressure (TAP) tool will be attached at the bottom of the tool string to measure borehole temperature, tool acceleration, and hydrostatic pressure in situ.

Formation MicroScanner–Dipole Sonic Imager Tool String

The FMS-sonic tool string has two main components:

- The Dipole Sonic Imager (DSI) measures a full waveform, including compressional wave (*P*-wave), shear wave (*S*-wave), and Stoneley wave (*St*-wave). This tool provides information related to the seismic structure of the upper oceanic crust.
- The FMS consists of four orthogonal pads with 16 electrodes on each pad. The FMS tool obtains a high-resolution microresistivity image of the borehole wall, which is useful for identification of volcanic units and tectonic features (e.g., the presence of fractures and faults and their orientations). The FMS tool includes a General Purpose Inclinometry Tool (GPIT), which provides tool acceleration and fluxgate magnetometer measurements that are used to orient the microresistivity images. The FMS arms are also used as calipers for hole size estimation. A Scintillation Gamma Ray Tool (SGT) is included in this tool string to enable the FMS measurements to be correlated with other logging tool runs and true depths of core features to be established.

Ultrasonic Borehole Imager

The UBI measures the amplitude and transit time of an acoustic wave propagated into the formation. It provides high-resolution images with 100% borehole wall coverage, allowing detection of small-scale fractures. The GPIT is deployed with the UBI and enables borehole images, fractures, and other structural features to be oriented. This can provide important information on the local stress field and borehole geometry even within casing. An SGT is included in this tool string to allow correlation with other logging runs for establishing consistent depth estimates.

Borehole Magnetometer

The Göttingen Borehole Magnetometer (GBM) that was successfully deployed during basement drilling during ODP Leg 197 and IODP Expedition 305 has been requested as a third-party tool for Expeditions 309 and 312. This tool has three fluxgate sensors that measure three orthogonal components of the magnetic field. The tool includes a gyroscope, which measures the tool rotation during data acquisition and allows the orientation of the tool to be determined. The data from the magnetometer will be used to monitor changes in the magnetic properties of the oceanic lithosphere as well as changes in paleomagnetic direction, primary objectives of the Site 1256 experiment. Although deployment of the GBM is contingent on availability of the tool and funds, we expect that the Joint Oceanographic Institute (JOI) logging contractors will support an experiment that is a named priority in the IODP Initial Science Plan.

Three-Component Well Seismic Tool

The three-component Well Seismic Tool (WST-3) records acoustic waves generated by an air gun located near the sea surface. It provides a complete checkshot survey, a depth-traveltime plot, and accurate estimates of drilling depth. A generator-injector air gun positioned over the side of the *JOIDES Resolution* will be used as the seismic source.

SAMPLING STRATEGY

Shipboard and shore-based researchers should refer to the interim IODP Sample, Data, and Obligations policy posted on the Web at **iodp.tamu.edu/curation/policy.html.** 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. As Expeditions 309 and 312 are both execution of the same proposal, we expect to consider the seagoing participants from both cruises as well as any approved shore-based researchers for either cruise as a single science party. Therefore, the Sample Allocation Committee (SAC) will consist of all four Co-Chief Scientists, both Staff Scientists, the IODP onshore Curator, and the curatorial representatives onboard the ship. This team will work with the entire science party from both expeditions to formulate a specific sampling plan for shipboard and postcruise sampling.

Owing to the short planning window for these expeditions, in order to coordinate all shipboard sampling shipboard scientists from both expeditions are expected to submit sample requests (**iodp.tamu.edu/curation/samples.html**) as soon as possible. Following good practice established during Leg 206, we strongly encourage collaboration among the shipboard and shore-based scientists so that the best use is made of the recovered core. Postcruise analytical programs should be coordinated to ensure that the full range of geochemical, magnetic, and physical property studies are undertaken on a representative sample suite. Sampling all but the most critical intervals will take place on board the ship, and, as few scientists will sail on both expeditions, scientists are encouraged to establish collaborations before Expedition 309 sails so that they have an interested party or group who can sample appropriate material during both cruises.

Based on sample requests (shipboard and shore based), the SAC will prepare a tentative sampling plan. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expeditions.

For the purpose of developing sample requests, participating scientists could expect to receive on the order of 25–100 samples of no more than 25 cm^3. This is based on historic precedent from ODP designed to enable scientists to complete a research program and meet the established publication deadlines. For these expeditions, all personal sample frequencies and sample volumes taken from the working half of the core must be justified on a scientific basis and will be dependent on core recovery, the full spectrum of other requests, and the project objectives. Postcruise research projects that require more frequent sampling or larger sample volumes should be further justified in sample requests. Some redundancy of measurement is unavoidable and even encouraged, but minimizing redundancy of measurements among the shipboard party and identified shore-based collaborators when recovery is sparse will be a factor in evaluating sample requests.

If some critical intervals are recovered (e.g., mineralization, veins, dikes or glassy margins, thin gabbroic intervals, melt lenses, etc.), 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. Time estimates for Superfast Spreading Rate Crust 2 and 3 (Expeditions 309 and 312).

Water depth (mbrf)	Operations description (mbsf)	Transit (days)	Drilling (days)	Logging (days)
	Sea voyage from Balboa, Panama, to Hole 1256D, 823 nmi @ 10.5 kt	3.3		
3645	Hole 1256D: - Locate and reenter hole - Temperature measurement - Water sample - Wireline logging			2.5
	Rotary core (RCB) from 752 to 1360 mbsf		30.4	
	Wireline logging: - Triple combo - Formation MicroScanner–Dipole Sonic Imager - Ultrasonic Borehole Imager - GBM Magnetometer - Well Seismic Tool			4.5
	Sea voyage from Hole 1256D to Balboa, Panama, 823 nmi @ 10.5 kt	3.3		
	Subtotals:	6.6	30.4	7.0
	Total operating days Expedition 309:		44.0	
	Sea voyage from Balboa, Panama, to Hole 1256D, 823 nmi @ 10.5 kt	3.3		
3645	Hole 1256D: - Locate and reenter hole - Temperature measurement - Water sample			
	Rotary core (RCB) from 1360 to 1960 mbsf		30.5	
	Wireline logging: - Triple combo - Formation MicroScanner–Dipole Sonic Imager - Ultrasonic Borehole Imager - GBM Magnetometer - Well Seismic Tool			4.5
	Sea voyage from Hole 1256D to Balboa, Panama, 823 nmi @ 10.5 kt	3.3		
	Subtotal:	6.6	30.5	4.5
	Total operating days Expedition 312:		41.6	

Table T2. Contingency operations time estimates.

Operation	Time (hours)	Time (days)	Total
Open hole to 500 m subbasement and install 750 m of 10.75 inch casing			
Run in hole	10.50	0.44	0.44
Open hole from 9.875 to 18.5 inches	483.90	20.16	20.60
Bit change	212.92	8.87	29.47
Pull out of hole	10.50	0.44	29.91
Make up casing string	24.00	1.00	30.91
Run in hole with casing	16.00	0.67	31.58
Run casing	22.00	0.92	32.49
Cement and R/T	24.00	1.00	33.49
Drill out cement	4.00	0.17	33.66
Trip	12.00	0.50	34.16
Install new reentry cone and 20 and 16 inch casing			
Jet 20 inch casing	30.60	1.3	
Pull out of hole	9.70	0.4	1.7
Make up, run in hole, reenter	10.00	0.4	2.1
Open hole 20 m subbasement	52.00	2.1	4.3
Pull out of hole	10.00	0.4	4.7
Makeup 270 m of 16 inch casing	8.00	0.3	5.0
Run in hole and reenter	8.60	0.4	5.4
Land casing	9.00	0.4	5.7
Cement casing	0.25	0.0	5.8
Clear seafloor	3.50	0.1	5.9
CADA on surface	7.75	0.3	6.2
Makeup bit and RCB bottom-hole assembly	1.50	0.1	6.3
Run in hole and reenter	8.50	0.4	6.6
To top of cement	3.25	0.1	6.8
Drill out cement	4.00	0.2	6.9
Pull out of hole	9.00	0.4	7.3
Single-bit holes (100–150 m subbasement)			
Run in hole	10.50	0.4	0.4
Core to bit destruction	85.00	3.5	3.9
Drop bit, log	24.00	1.0	4.9
Multi-bit holes (200–300 m subbasement)			
Run in hole	10.50	0.4	0.4
Core to 50 hours on bit	65.00	2.7	3.1
Drop free-fall funnel; pull out of hole	10.00	0.4	3.5
Run in hole	10.50	0.4	3.9
Core to bit destruction	85.00	3.5	7.4
Drop bit, log	36.00	1.5	8.9
Log Hole 504B			
Transit to Hole 504B	60.00	2.5	2.5
Run in hole	10.00	0.4	2.9
Water Sampling Temperature Probe	4.00	0.2	3.1
Triple combo, Formation MicroScanner-sonic, Ultrasonic Borehole Imager, GBM magnetometer, Well Seismic Tool	108.00	4.5	7.6
Deepen Hole 896A			
Run in hole	10.00	0.4	0.4
Water Sampling Temperature Probe	4.00	0.2	0.6
Core to 50 hours on bit	65.00	2.7	3.7
Logging	108.00	4.5	8.2

Note: Add 3.7 days and 100 m penetration per bit run.

Figure F1. **A.** Basement age versus depth of basement penetration for scientific drill holes deeper than 50 m drilled into in situ ocean crust formed at the mid-ocean ridges. **B.** Depth of penetration of drill holes into in situ basement clustered by broad spreading rate subdivisions where slow < 40 mm/y < moderate < 80 mm/y < fast. Note the boundaries between the erupted lavas, dike–lava transition zone, and the sheeted dike complex/upper gabbro boundary are placed at arbitrary depths based loosely on the Hole 504B stratigraphy. Predictions based on marine seismic reflection studies indicate that the combined thickness of the lava-dike sequences should decrease with spreading rate but are yet to be tested, and whether it is the dikes or lavas that are thinned is so far unknown. Black lines = DSDP drill holes, dark blue lines = ODP drill holes, red lines = Holes 1256C and 1256D drilled into basement during Leg 206.

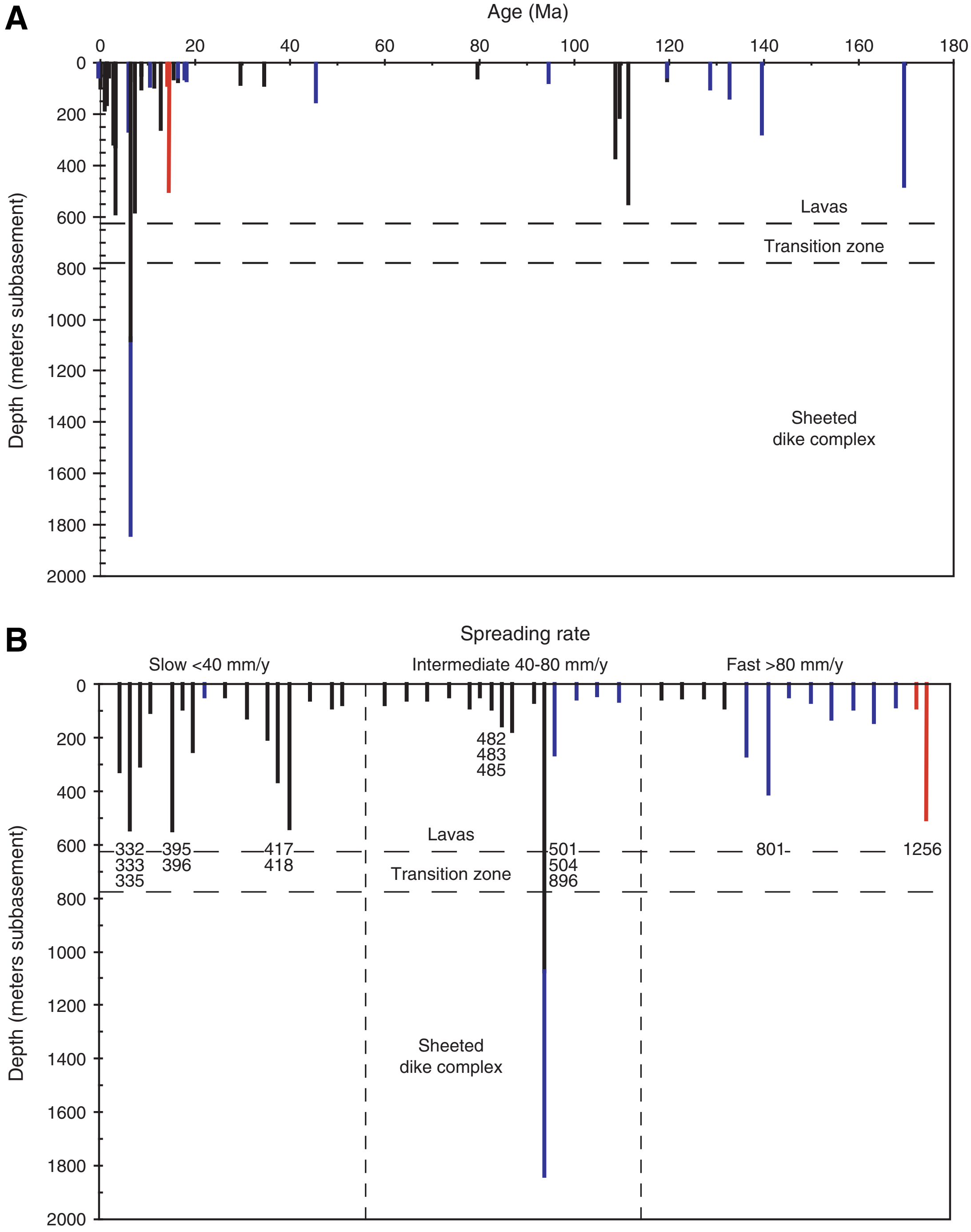


Figure F2. Age map of the Cocos plate and corresponding regions of the Pacific plate. Isochrons at 5 m.y. intervals have been converted from magnetic anomaly identifications according to the timescale of Cande and Kent (1995). Selected DSDP and ODP sites that reached basement are indicated. The wide spacing of 10–20 m.y. isochrons to the south reflects the extremely fast (200–220 mm/y) full spreading rate (modified from Shipboard Scientific Party, 2003). FZ = fracture zone.

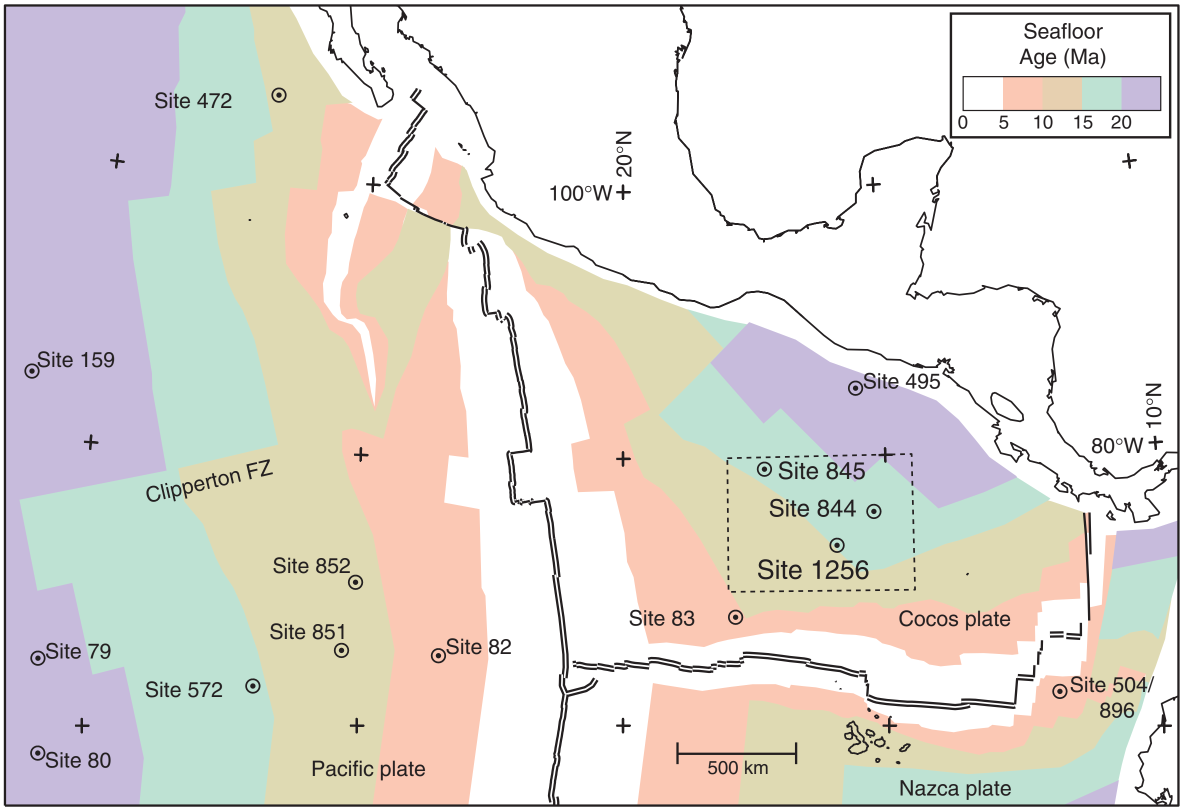


Figure F3. Details of isochrons inferred from magnetic anomalies near Site 1256. Shading shows normal magnetic polarity, based on digitized reversal boundaries (small circles, after Wilson, 1996). Bold line shows location of Guatemala Basin multichannel seismic tracklines from the site survey conducted in March–April 1999. Anomaly ages: 5A = ~12 Ma, 5B = 15 Ma, and 5D = ~17 Ma (from Shipboard Scientific Party, 2003).

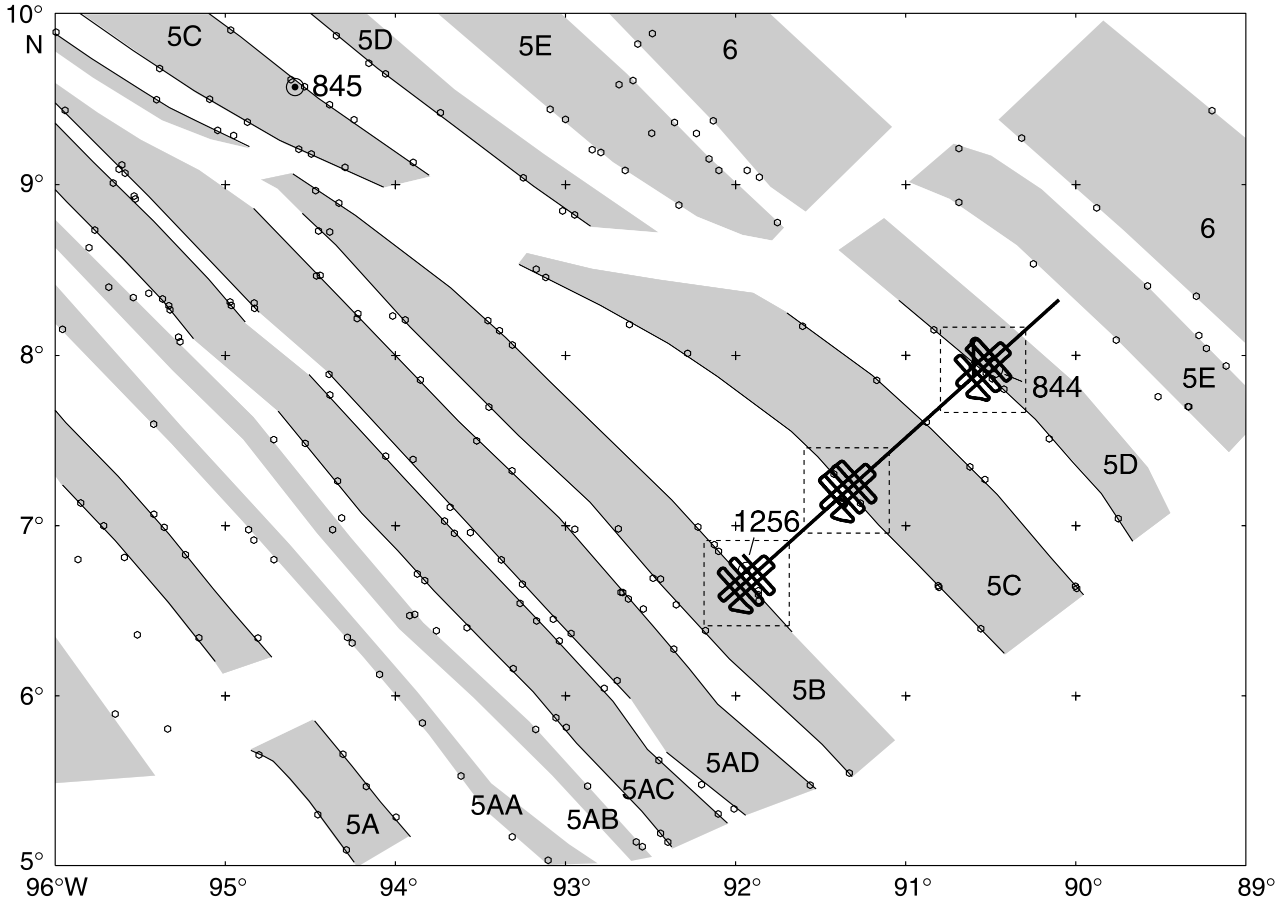


Figure F4. Depth to axial low-velocity zone plotted against spreading rate (modified from Purdy et al., 1992, and Carbotte et al., 1997). Depth versus rate predictions from two models of Phipps Morgan and Chen (1993) are shown, extrapolated subjectively to 200 mm/y (dashed lines). Penetration to date in Holes 504B and 1256D is shown by solid vertical lines, and planned deepening for Expeditions 309 and 312 are indicated. MAR = Mid-Atlantic Ridge, EPR = East Pacific Rise, JdF = Juan de Fuca Ridge, Lau = Valu Fa Ridge in Lau Basin, CRR = Costa Rica Rift.

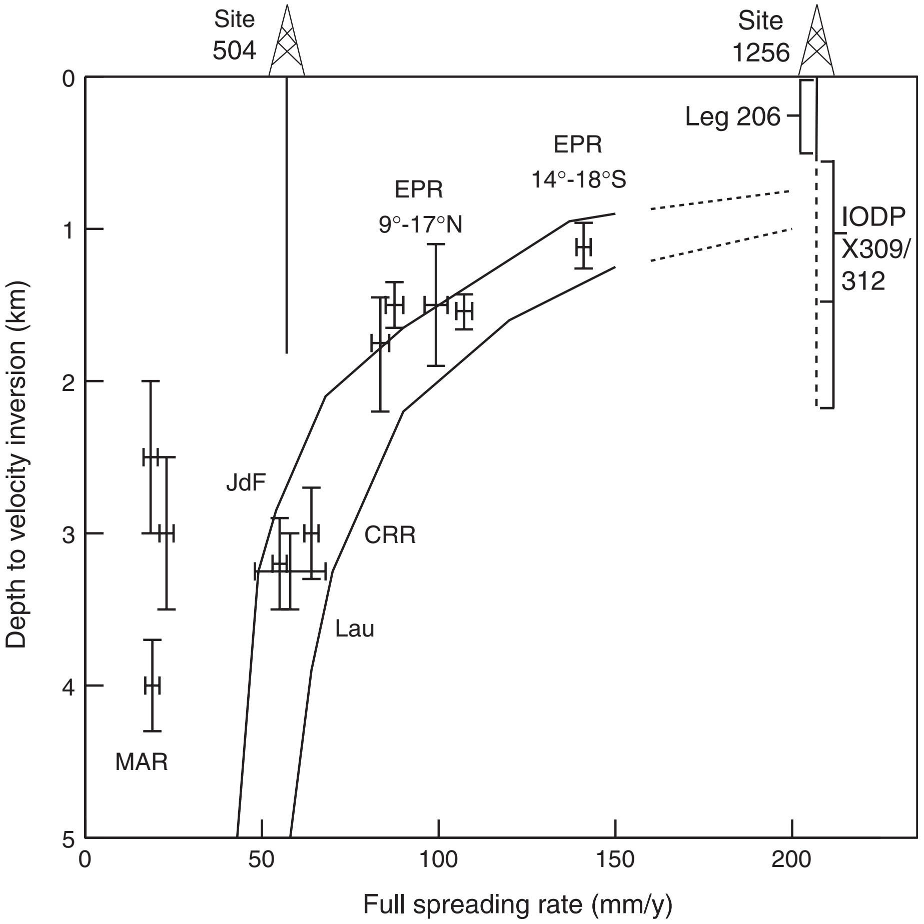


Figure F5. Depth versus time graph for drilling and wireline logging operations for Expeditions 309 and 312. Solid line shows the current depth of Hole 1256D. Horizontal lines show the range of depths at which axial low-velocity zones, now frozen as gabbros, are predicted to occur. Drilling rates and pipe-trip times as calculated in Table **T1.** RCB = rotary core barrel.

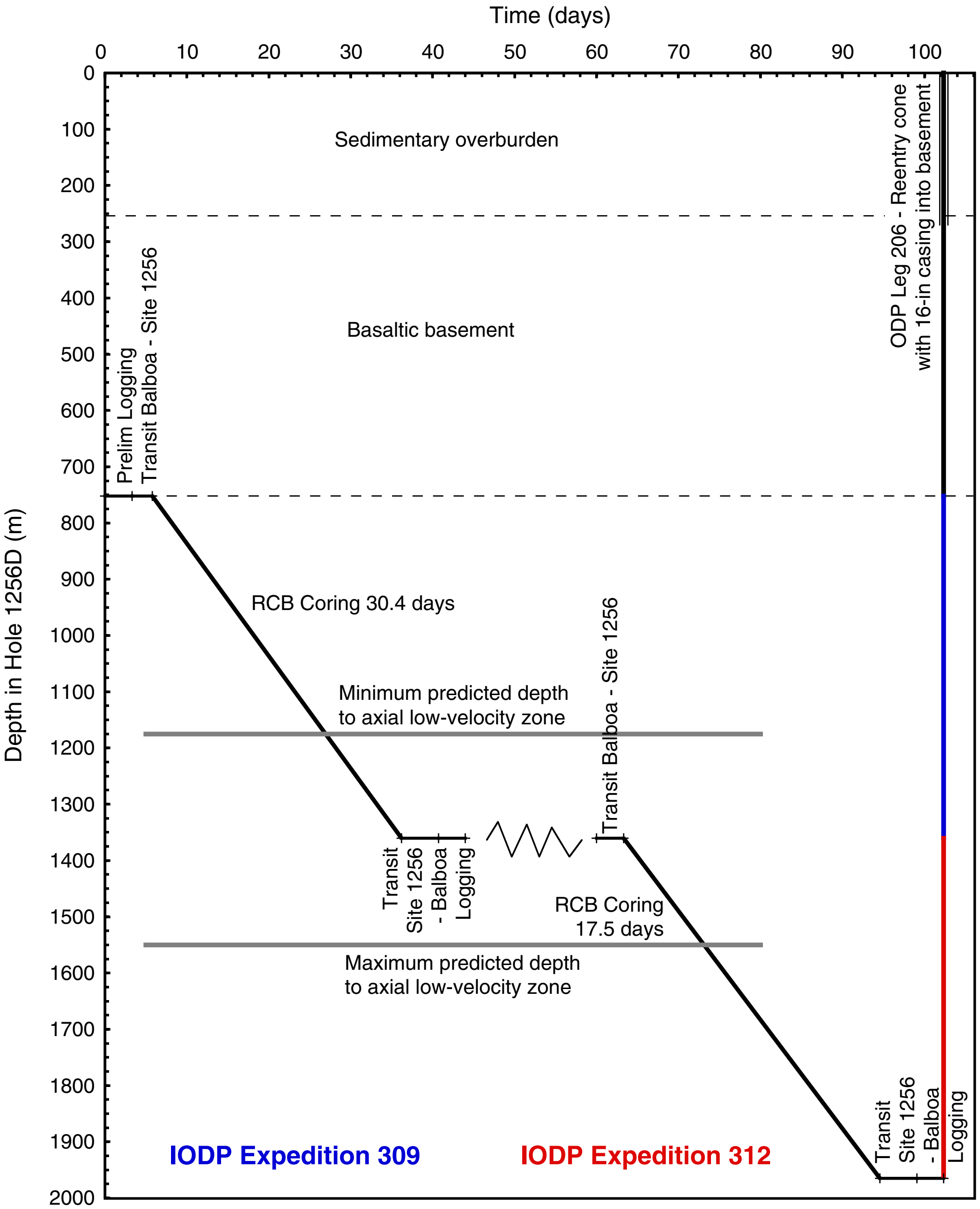


Figure F6. Bathymetry and site survey track map for Site 1256 and local, alternate single- or multibit penetration holes. Abyssal hill relief of as much as 100 m is apparent in the southwest portion of the survey area; relief to the northeast is more subdued. MCS = multichannel seismic, OBH = ocean bottom hydrophone.

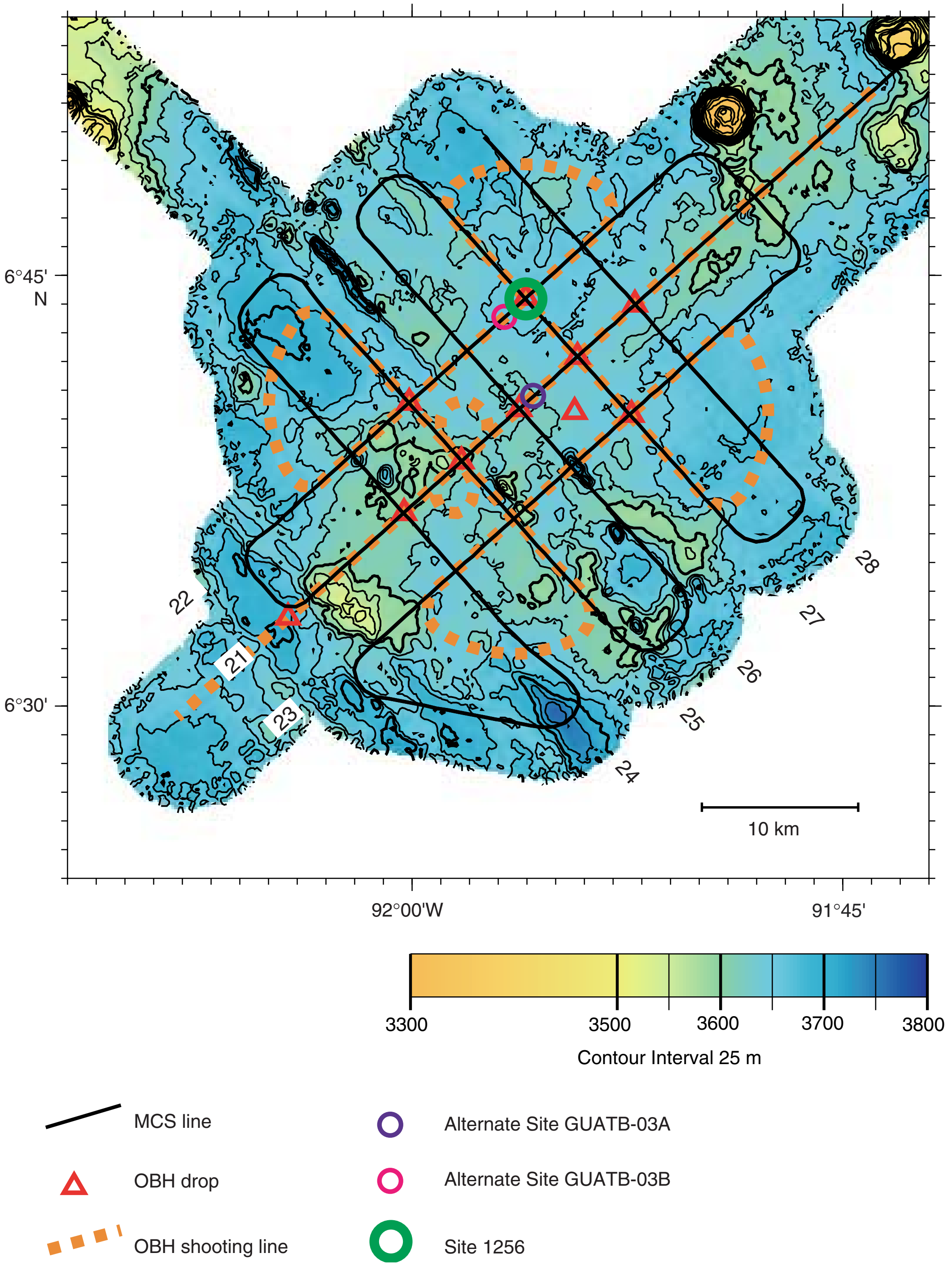


Figure F7. Diagram illustrating a comparison between lithostratigraphy determined by core descriptions (left column) and from downhole wireline logging data (right column). Stratigraphic columns are keyed to the color codes in the pie charts.

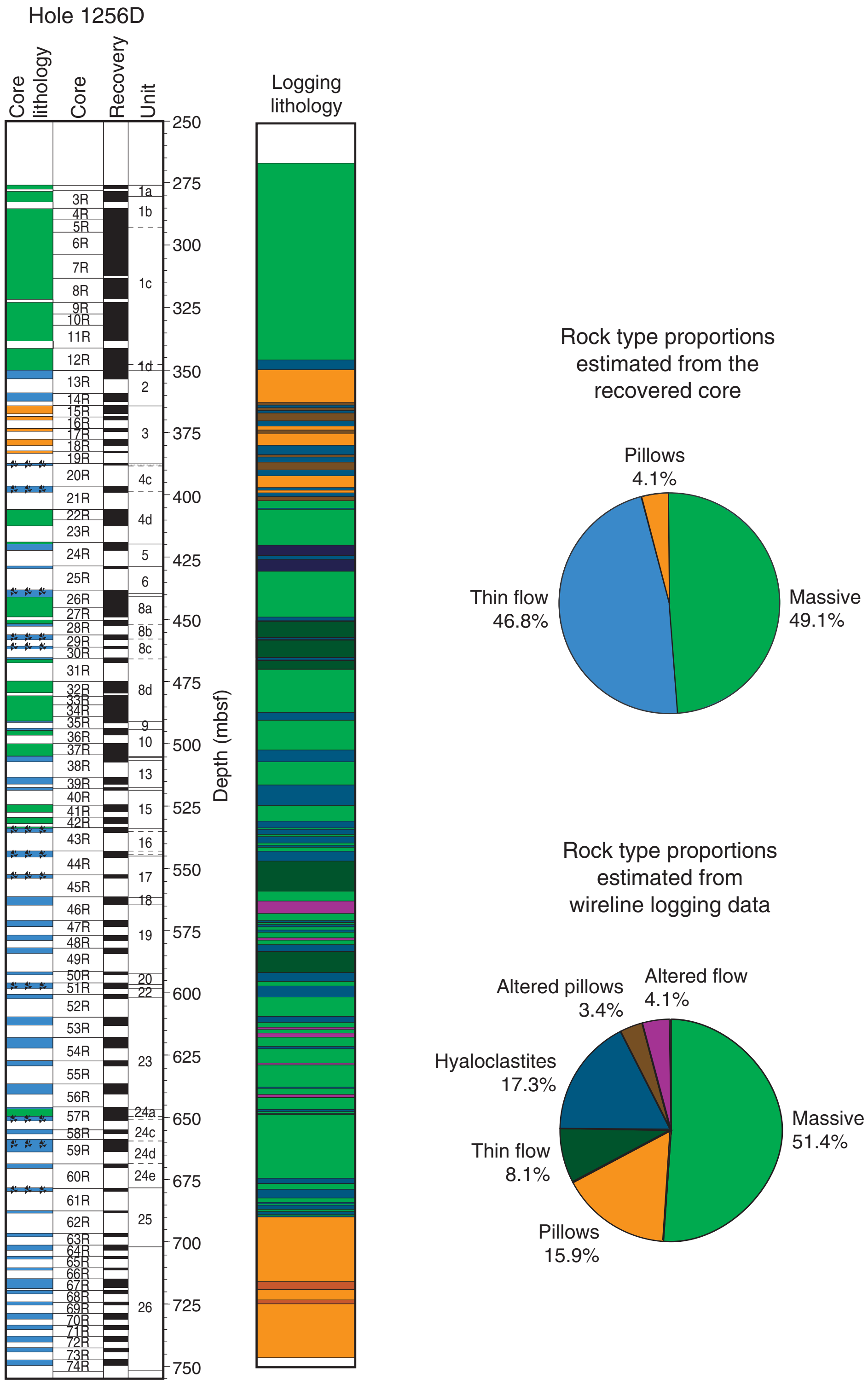


Figure F8. Stacked, migrated section of MCS data from seismic Line 22, showing positions of primary drill Site 1256 and alternate Site GUATB-03B. Crossing positions of Lines 24–28 are labeled.

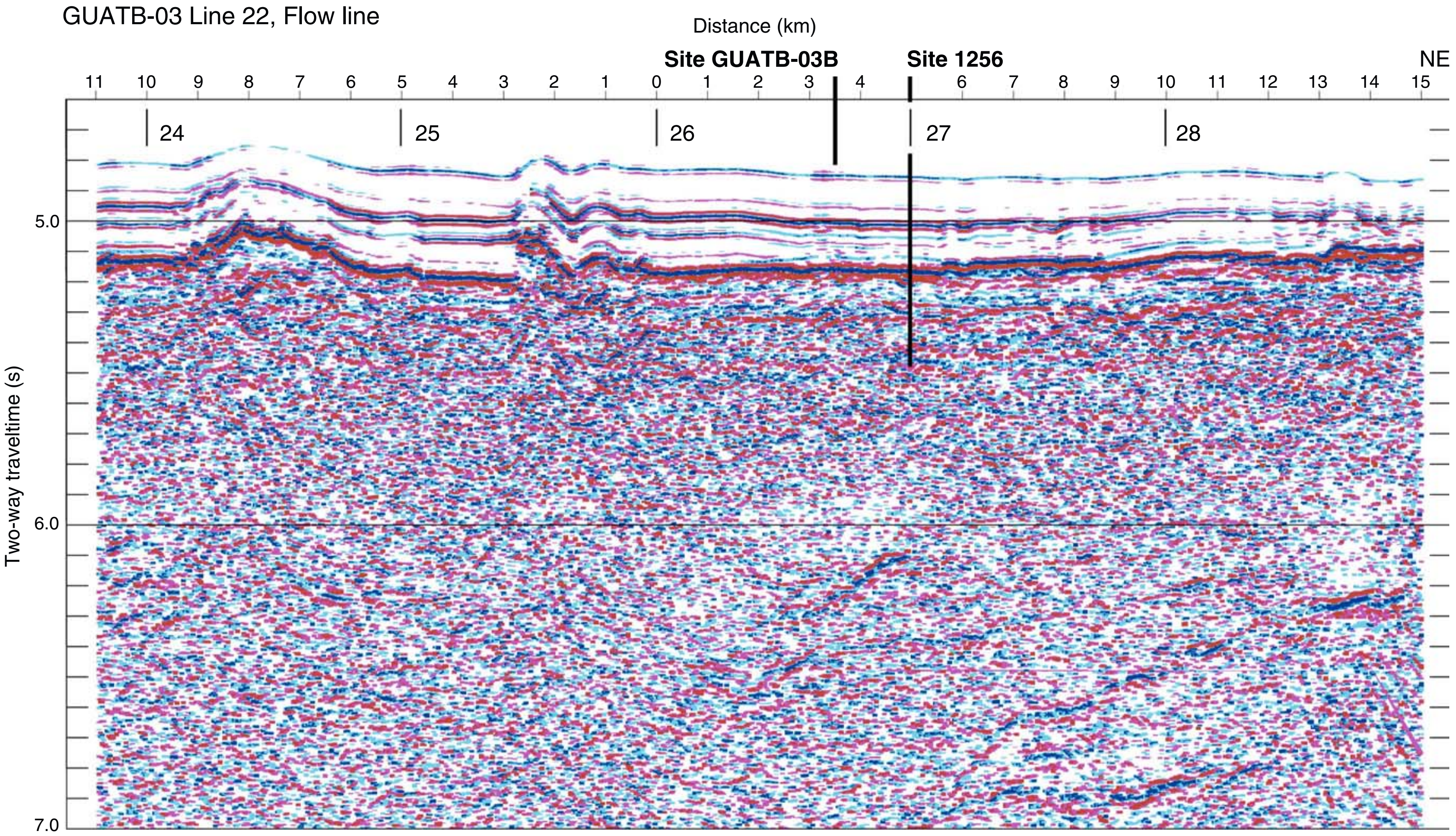


Figure F9. Stacked, migrated section of MCS data from Line 27, showing the primary drill Site 1256 and crossing positions of Lines 21–23. The bright reflector at 5.5–5.7 s near Line 21 crossing may be a thrust fault.

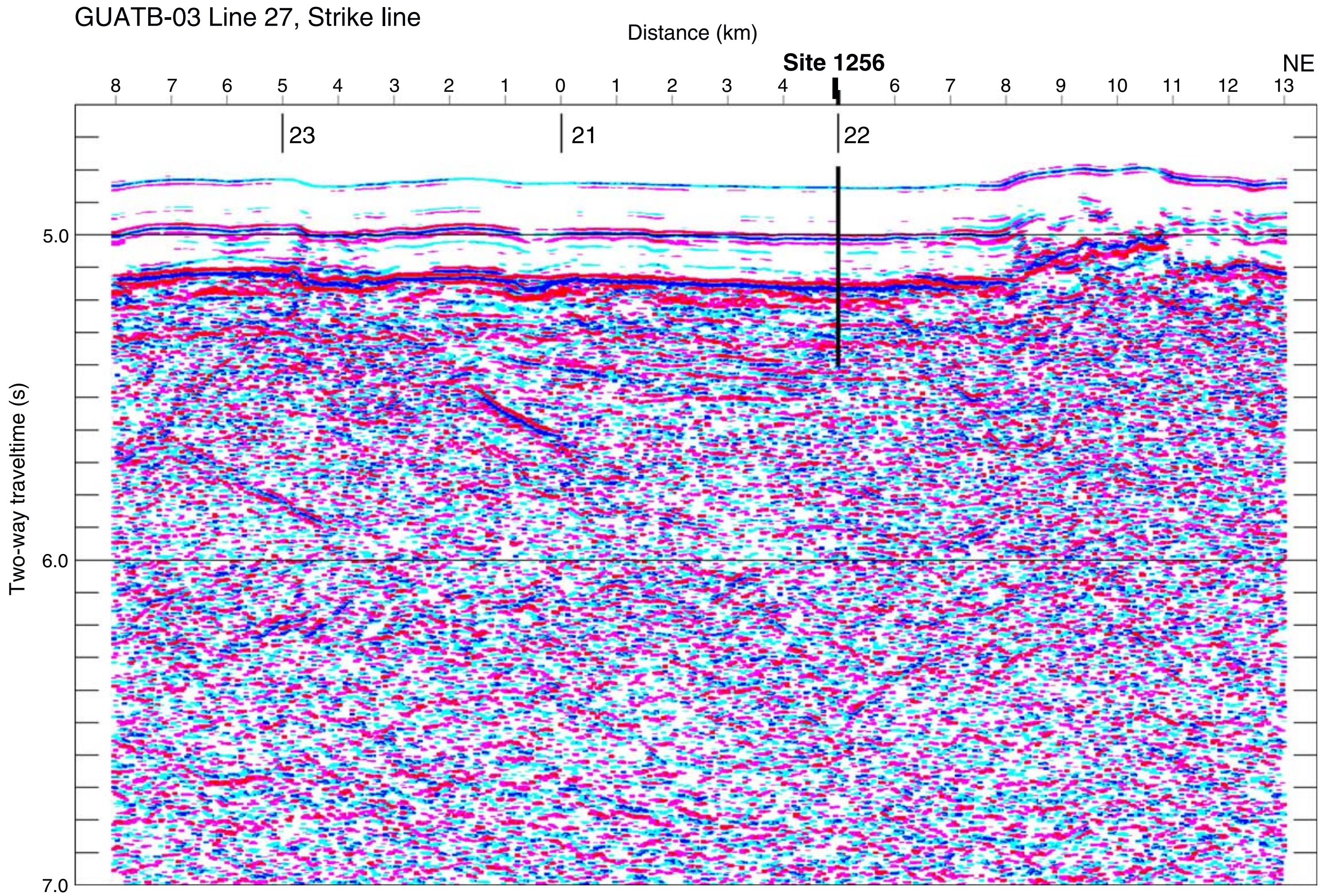


Figure F10. Stacked, migrated section of MCS data from Line 21, showing the alternate drill Site GUATB-03A and crossing positions of lines.

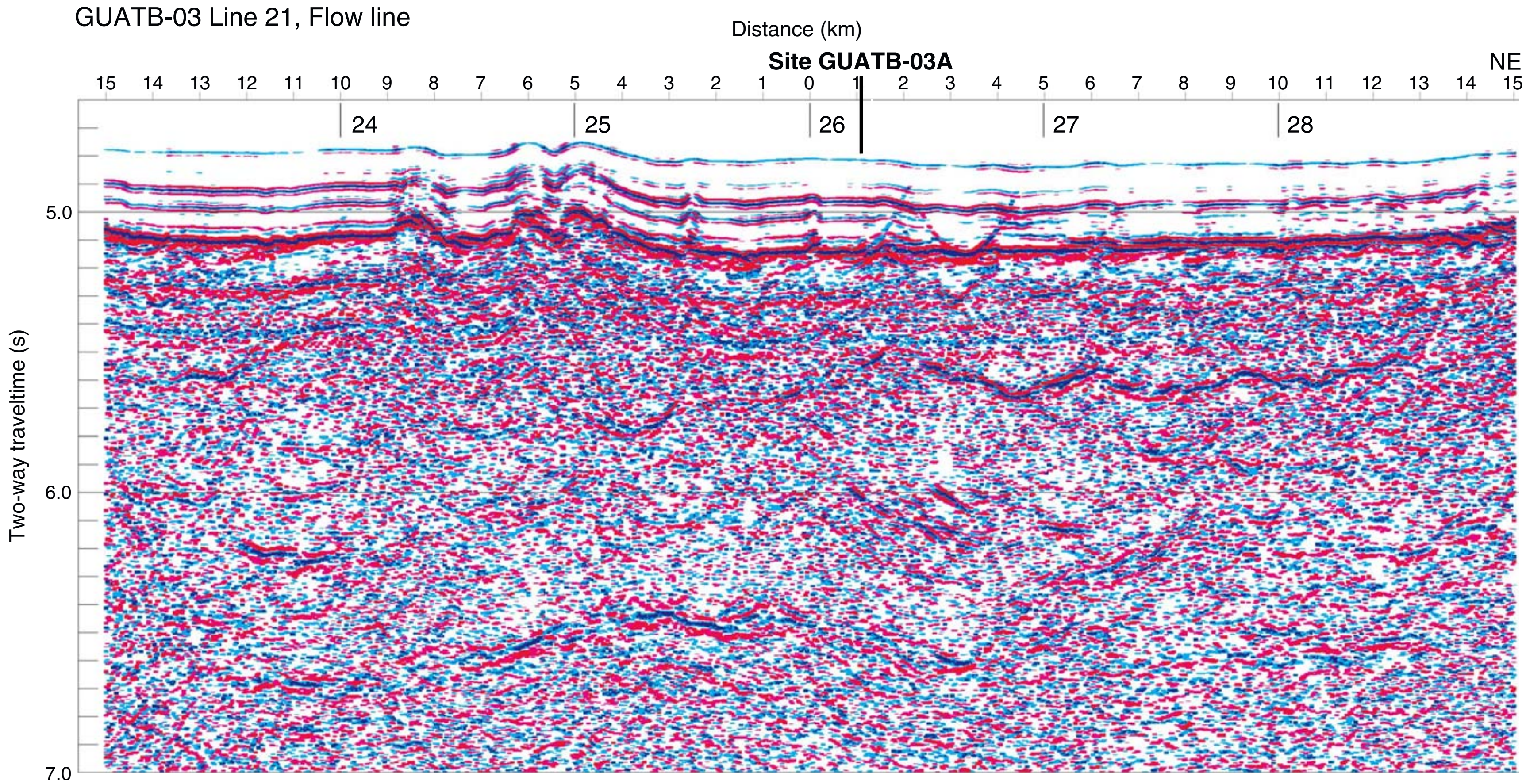
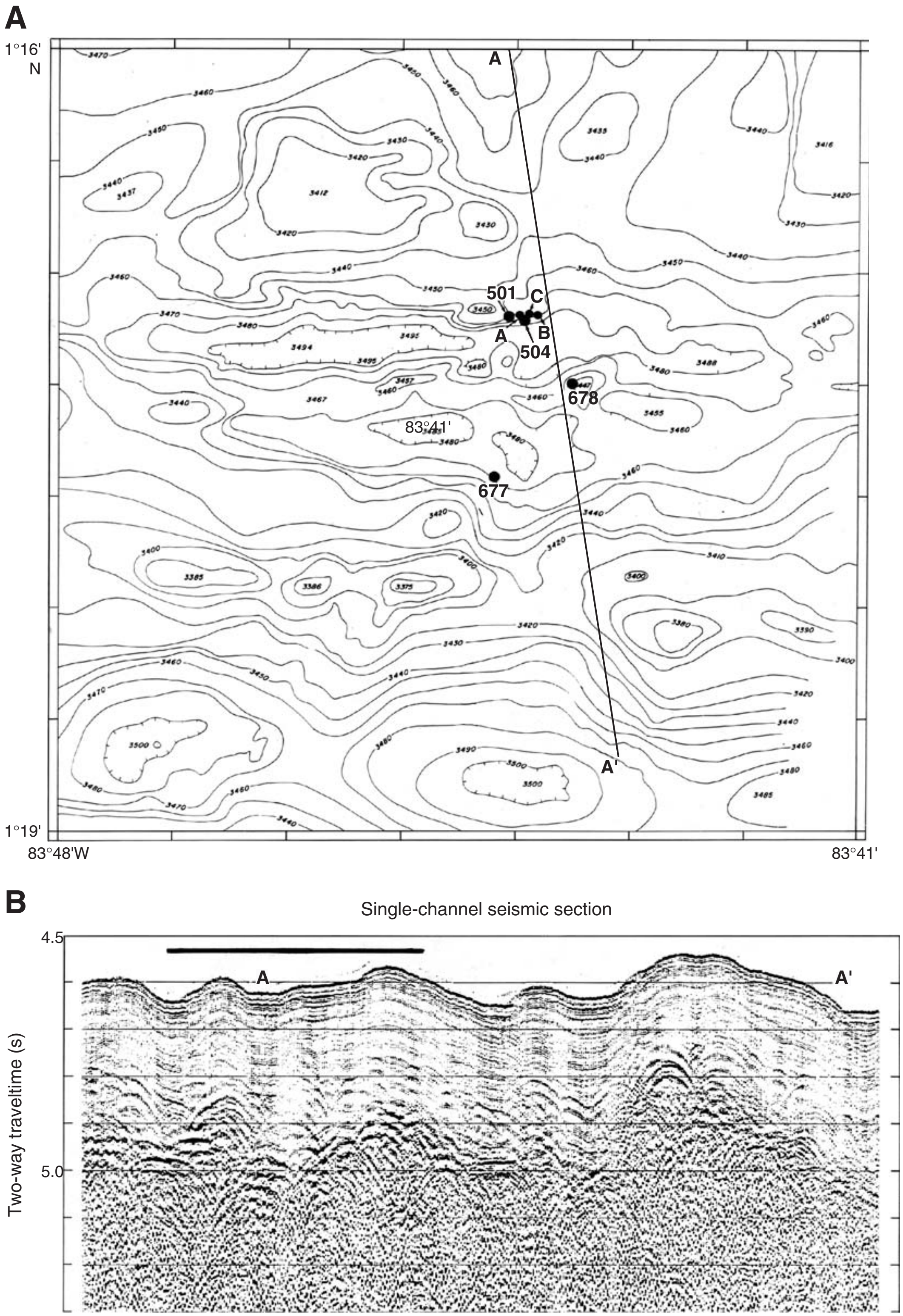


Figure F11. A. Contour map of seafloor bathymetry in the vicinity of Sites 504 and 896 (modified from Langseth et al., 1988). Line A–A′ shows the location of single-channel seismic section shown in **B.** Single-channel seismic section across Line A–A′ .



SITE SUMMARIES

Site 1256

Priority:	1
Position:	6°44.19′ N, 91°56.06′ W
Water depth (m):	3655
Sediment thickness (m):	252
Target drilling depth (mbsf):	As deep as possible
Approved maximum penetration (mbsf):	1700 (although EPSP notes also report approved as proposed and proposal requests >1700 m total penetration)
Survey coverage:	Acquired during *Ewing* cruise EW9903, March–April, 1999: • MCS with 480 channels, 10 air guns • Refraction shooting 20 air guns recorded on ocean bottom hydrophones (OBHs) • 3.5 kHz reflection • Hydrosweep multibeam bathymetry Site 1256 is at the crossing of EW9903 Lines 22 and 27 (see Figures **F8, F9**)
Objective:	• Provide a reference with in situ samples through the extrusive volcanic and feeder dike section and into gabbroic rock normal, intact oceanic crust formed at very fast spreading rate at 15 Ma to constrain models of formation and alteration of oceanic crust • Maintain a “legacy hole” available for future deepening
Drilling and logging program:	Continuous coring as deep as possible

Logging program:	• WSTP on arrival
	• Triple combo to determine borehole condition. If borehole has notably deteriorated we may elect to conduct more logging runs with additional tools
	• Full logging suites planned at the end of each expedition include
	  • Triple combo
	  • FMS/sonic
	  • BGR borehole magnetometer: oriented magnetic field measurements
	  • UBI: acoustic borehole images
	  • WST: normal-incidence vertical seismic profiling
	• Incremental logging runs may be implemented if hole conditions warrant

Nature of rock anticipated:	Basalt, diabase, and gabbro

SITE SUMMARIES (CONTINUED)

Site GUATB-03A

Priority:	2 (Alternate site)
Position:	6°40.64′ N, 91°55.94′ W
Water depth (m):	3621
Sediment thickness (m):	240
Target drilling depth (mbsf):	350–600
Approved maximum penetration (mbsf):	Approved for unlimited penetration according to ODP Leg 206 *Scientific Prospectus;* same approval requested for IODP Expeditions 309 and 312
Survey coverage:	Acquired during *Ewing* cruise EW9903, March–April, 1999: • MCS with 480 channels, 10 air guns • Refraction shooting 20 air guns recorded on OBHs • 3.5 kHz reflection • Hydrosweep multibeam bathymetry Site GUATB-03A is on EW9903 Line 21 between Lines 26 and 27 (see Figure **F10**)
Objective:	• Establish regional variation in upper crustal processes, lithologic structure, and seawater interactions • Determine the extent of the massive lava flow encountered in Holes 1256C and 1256D to constrain the size of off-axis eruptions and drilling further afield in the GUATB-03 survey region
Drilling and logging program:	• Single bit to destruction or free-fall funnel deployment for an additional bit trip if recovery warrants • Because the sediment cover in the area has been documented in multiple cores, we request the option to wash through the sediment column a begin coring at the sediment/basement interface
Logging program:	• Triple combo • FMS-sonic • BGR borehole magnetometer: oriented magnetic field measurements • UBI: acoustic borehole images
Nature of rock anticipated:	Pelagic sediment overlying basalt

SITE SUMMARIES (CONTINUED)

Site GUATB-03B

Priority:	2 (Alternate site)
Position:	6°43.64′ N, 91°56.66′ W
Water depth (m):	3650
Sediment thickness (m):	240
Target drilling depth (mbsf):	350–600
Approved maximum penetration (mbsf):	Approved for unlimited penetration according to ODP Leg 206 *Scientific Prospectus;* same approval requested for IODP Expeditions 309 and 312.
Survey coverage:	Acquired during *Ewing* cruise EW9903, March–April, 1999: • MCS with 480 channels, 10 air guns • Refraction shooting 20 air guns recorded on OBHs • 3.5 kHz reflection • Hydrosweep multibeam bathymetry Site GUATB-03B is on EW9903 Line 22 between Lines 26 and 27 (see Figure **F8**)
Objective:	• Establish regional variation in upper crustal processes, lithologic structure, and seawater interactions • Determine the extent of the massive lava flow encountered in Holes 1256C and 1256D to constrain the size of off-axis eruptions and drilling further afield in the GUATB-03 survey region
Drilling and Logging program:	• Single bit to destruction or free-fall funnel deployment for an additional bit trip if recovery warrants • Because the sediment cover in the area has been documented in multiple cores, we request the option to wash through the sediment column a begin coring at the sediment/basement interface
Logging program:	• Triple combo • FMS-sonic • BGR borehole magnetometer: oriented magnetic field measurements • UBI: acoustic borehole images
Nature of rock anticipated:	Pelagic sediment overlying basalt

SITE SUMMARIES (CONTINUED)

Hole 504B

Priority:	2 (Alternate site)
Position:	1°13.611′ N, 83°43.818′ W (see Figure **F11**)
Water depth (m):	3463
Sediment thickness (m):	274.5
Target drilling depth (mbsf):	None
Approved maximum penetration (mbsf):	None
Objective:	• Acquire FMS-sonic and UBI data from as much of the borehole as possible • Collect water sample and temperature profile first, followed by caliper (triple combo) to determine borehole stability

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