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Reports on Deep Earth Sampling and Monitoring

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Editorial Preface

Dear Reader:

We appreciate that many of you have commented favorably on the first two issues of Scientific Drilling. Respondents have frequently expressed delight, and often surprise, at learning about the remarkable breadth and scope of scientific projects that employ drilling as a means of studying the Earth and its environments. This third issue of the journal is no exception, spanning topics from extraterrestrial impact events over gas hydrates to fluid flow in both shallow and deep crustal settings. In addition, we are pleased to introduce in this issue yet another international scientific drilling program—ANDRILL. This Antarctic drilling program will recover sediment cores from beneath the ice shelf, tracking the history of Antarctic ice-sheet variation and evolution back in time to well before the date of the oldest preserved ice in Antarctica.

We editors are no less impressed than the readers by the diversity of scientific drilling and the technology applied, but also note that, despite differences in technology and organization, there is a remarkable coincidence, if not identity, of scientific themes addressed by the many projects. For example, in this issue we report on drilling supported studies of seismogenesis in deep South African mines, a project naturally complementing the ICDP drilling of the San Andreas Fault in California and the IODP Nankai Trough project off the shore of Japan. A most striking feature is how lake drilling in climatically sensitive areas complements the deep sea record of climatic change over geological time. This is important for underpinning predictive climatic models, not only by expanding the global array of observations, but also by providing direct evidence for the impact of climate changes on continental settings outside the polar regions. The most detailed history of climatic changes is contained within ice cores from the Arctic and Antarctic ice shields, and we intend to expand the scope of our journal by featuring reports on this topic in the International Polar Year 2007–2008.

We conclude that Scientific Drilling has proven that the whole can be greater than the sum of its parts, and we hope that this publication can prove to be a model for future collaborations in scientific planning, developments in drilling-related technology, and efficiency in the distribution of samples and data. Enjoy your reading!

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Front Cover: *Main:* Drilling operations at Lake Petén Itzá, Guatemala, (see article on page 25). Photograph by Mark Brenner, University of Florida, Gainesville, Fla.
Left inset: Gas hydrates found during IODP Expedition 311 (see article on page 18).

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IODP is an international marine research drilling program dedicated to advancing scientific understanding of the Earth by monitoring and sampling subsea-floor environments. Through multiple drilling platforms, IODP scientists explore the program's principal themes: the deep biosphere, environmental change, and solid earth cycles.

ICDP is a multi-national program designed to promote and coordinate continental drilling projects with a variety of scientific targets at drilling sites of global significance.

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Contents

Science Reports

IODP Expeditions 304 & 305 Characterize the Lithology, Structure, and Alteration of an Oceanic Core Complex

by Benoit Ildefonse, Donna Blackman, Barbara E. John, Yasuhiko Ohara, D. Jay Miller, Christopher J. MacLeod, and the IODP Expeditions 304-305 Scientists

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Introduction and Goals

More than forty years after the Mohole Project (Bascom, 1961), the goal of drilling a complete section through *in situ* oceanic crust remains unachieved. Deep Sea Drilling Project – Ocean Drilling Program (DSDP-ODP) Hole 504B within the eastern Pacific (Alt et al., 1993) is the deepest hole ever drilled into ocean crust (2111 mbsf), but it failed to reach lower crustal plutonic rocks below the pillow basalts and sheeted dikes. IODP Expeditions 309 and 312 eventually recovered the long-sought transition from sheeted dikes into underlying gabbros by drilling into very fast-spreading Pacific crust (Wilson et al., 2006). The lithology and structure of oceanic crust produced at slow-spreading ridges are heterogeneous (e.g., Cannat et al., 1997) and offer unique drilling access to lower crust and upper mantle rocks. After ODP Hole 735B penetrated 1500 m of gabbro at the Southwest Indian Ridge (Dick et al., 2000), IODP Expeditions 304 and 305 recently recovered just over 1400 m of little-deformed, gabbroic lower crust from a tectonic window along the slow-spreading Mid-Atlantic Ridge.

IODP Expeditions 304 and 305 at the Atlantis Massif, Mid-Atlantic Ridge 30°N, were designed to investigate the processes that control oceanic core complex (OCC) formation and exposure of lower crust and upper mantle rocks in young (<2 Ma) oceanic lithosphere accreted at slow-spreading ridges. The corrugated, central portion of this domal massif (Fig. 1) displays morphologic and geophysical characteristics inferred to be representative of an OCC exposed via long-lived, low-angle, normal or detachment faulting (Cann et al., 1997; Blackman et al., 1998, 2004). Geophysical inter-

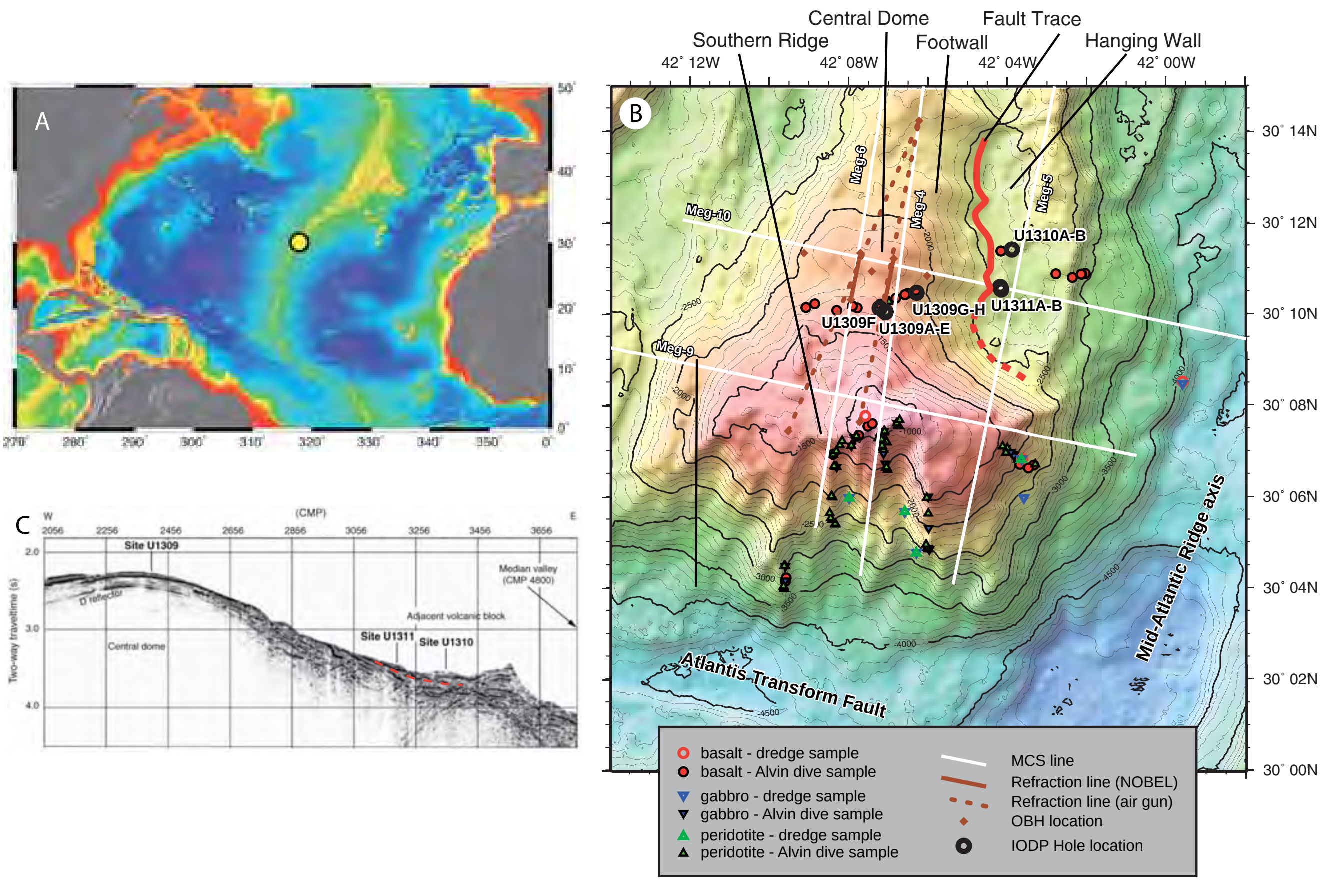

Figure 1. [A] Location of Expeditions 304 and 305. [B] Base map of Atlantis Massif showing prior geological and geophysical data coverage and location of drilling sites. Seismic reflection and refraction lines and seafloor mapping and sampling sites are shown. MCS = multi-channel seismic, OBH = ocean-bottom hydrophone. [C] MCS line Meg-10, stacked section showing D reflector and possible continuation of the detachment fault beneath the hanging wall (dashed red line).

pretations suggested that unaltered mantle rock occurred <1 km below the seafloor (Collins et al., 2003; Blackman et al., 2004; Canales et al., 2004), implying that drilling through an alteration front in ultramafic rocks could be achieved and that fresh mantle peridotite could be recovered at moderate depths. Additional objectives of drilling at the footwall concerned the dominant mechanism(s) of footwall uplift and the interactions between tectonics and magmatism in OCCs. Drilling within the hanging wall and through the detachment fault system was aimed at sampling and further constraining the latter and at assessing petrogenetic relationships between volcanic rocks in the hanging wall and potential source rocks recovered in the footwall.

We attempted drilling at three sites (Fig. 1 [C]), one in the footwall through the inferred detachment fault and two in the hanging wall, but we did not succeed in drilling the fractured basalt in the hanging wall. In contrast, Hole U1309D, in the footwall of the detachment fault, penetrated 1415.5 m below the seafloor, and recovery averaged 75% (IODP Expeditions 304-305 Scientists, 2005). Shallow holes on the footwall provided limited samples whose composition and structure support the hypothesis that the corrugated dome coincides with an exposed detachment fault.

Geological and Geophysical Background

The Atlantis Massif formed within the past 1.5–2 My. and was exhumed along a detachment fault exposed over an 8–10-km-wide, 15-km-long area that forms the elongate, doubly plunging domal seafloor morphology (Fig. 1). Adjacent basaltic rocks to the east are interpreted as part of a hanging-wall block above the detachment fault. Multi-channel seismic data (Canales et al., 2004) suggest that the fault system may dip gently under the seafloor at the base of the dome and continue at a shallow angle (<15°) beneath the eastern block toward the present-day ridge axis (Fig. 1C). The Southern Ridge is shallower than the central dome, shoaling to 700 m below sea level, and its corrugated surface extends eastward to the median valley wall.

Prior to IODP drilling, the core of the Atlantis Massif was inferred to comprise dominantly mantle peridotite. The peridotite-hosted, possibly serpentinization-driven Lost City hydrothermal vent field (Früh-Green et al., 2003; Kelley et al., 2005) is located just below the summit of the Southern Ridge, approximately 5 km south of Site U1309. Analysis of seismic refraction data across the central dome of the Atlantis Massif (Collins et al., 2003) indicated, at least locally, P-wave velocities of ~8 $km \cdot s^{-1}$ within several hundred meters below the seafloor, possibly indicative of pristine mantle rocks. Interpretation of multi-channel seismic reflection data suggested a major difference in structure between the outside (conjugate) corner lithosphere versus that hosting the Atlantis Massif (Canales et al., 2004). A strong reflector is visible at 0.2–0.5 s below much of the domal surface and coincides roughly with the depth below which mantle velocities were inferred from the seismic refraction data. One interpretation of this “D reflector” suggested that it marks an alteration front within the peridotite-dominated massif. The multi-channel seismic (MCS) processing employed by Canales et al. (2004) resulted in the D reflector being quite continuous across the dome. A subsequent study by Singh et al. (2004) using different processing parameters to emphasize deep reflectivity produced a less continuous, but still pervasive interval of reflectivity whose top generally coincided with Canales' D reflector. Modeling of sea-surface gravity and sparse seafloor data (Blackman et al., 1998, 2004; Nooner et al., 2003) suggests that rocks beneath the central and southern dome have densities 200–400 $kg \cdot m^{-3}$ greater than rock to either side.

Rock samples collected from the central dome by the manned submersible *Alvin* are dominated by angular talus and rubble of serpentinized peridotite, metabasalt, and limestone (Blackman et al., 2004). A few samples from the central dome show cataclastic deformation or are highly serpentinized or metasomatically altered peridotite. The protolith of most of the serpentinite sampled on the south wall (Fig. 1) is inferred to be harzburgite. Talc-rich fault rocks preserve textural and geochemical characteristics of their ultramafic protoliths (Boschi et al., 2006). Microstructural analysis of samples from the south wall (Schroeder and John, 2004) indicates ductile deformation initially at granulite facies, overprinted by semi-brittle and brittle deformation down to subgreenschist facies. The observations and sample distribution suggest that strong semi-brittle and brittle deformation is concentrated at shallow structural levels (~100 m beneath the domal surface) along the Southern Ridge (Schroeder and John, 2004; Karson et al., 2006). Rocks sampled from the hanging wall by manned submersible are wholly basalt (Blackman et al., 2004).

Drilling at the Atlantis Massif Reveals Dominantly Gabbroic Core

Igneous rocks recovered from Site U1309 span a broad range in composition, from the most primitive crustal rocks ever cored in slow-spreading oceanic lithosphere (Mg# up to ~90) to highly evolved rock types (Fig. 2). To a first order, the gabbroic section can be divided into two major igneous units (Johnson et al., 2005). The upper unit extends to ~600 mbsf and broadly shows an increase downhole in olivine-rich rock types, although the detailed lithostratigraphy is more complicated. There is a sharp decrease in whole-rock Mg# of the gabbros at ~600 mbsf (Fig. 2). Oxide-rich gabbros are concentrated in a zone between these upper and lower units. The lower unit also shows a general increase downhole in olivine-rich rock types, with oxide-rich intervals near the base of the hole. At least two thin, mantle-peridotite intervals are recognized in the upper 180 m of the section, implying that the gabbroic section recovered in Hole U1309D was in part intruded into mantle peridotite.

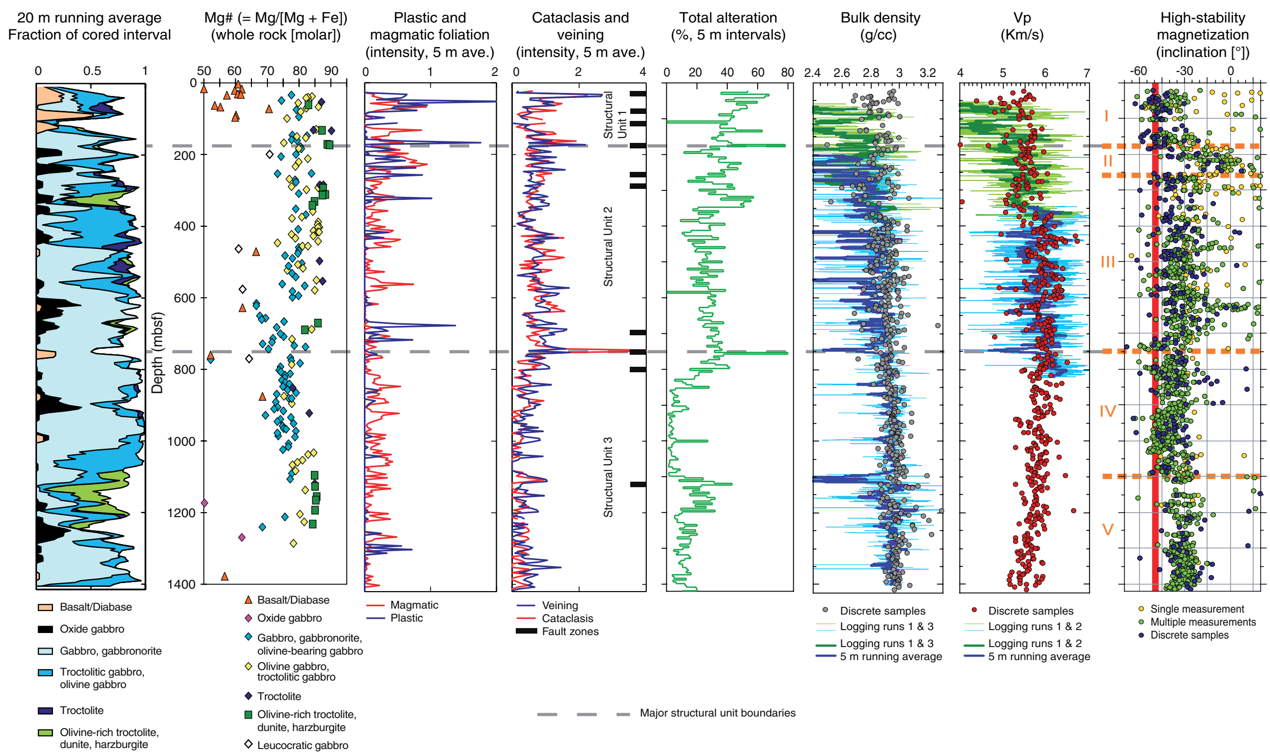

Figure 2. Downhole plots (Hole U1309D) of (left to right): lithology (20 m running average, white = no recovery), Mg#, plastic and magmatic foliation intensity (macroscopic description), cataclasis and veining intensity (macroscopic description), total alteration (macroscopic description), bulk density (from borehole and discrete sample measurements), compressional velocity (from borehole and discrete sample measurements), and inclination of stable remanent magnetization.

Holes U1309B and U1309D have interfingered lithologic units that vary in thickness from centimeters up to ~100–200 m where intrusive contacts are preserved. Contact relations where visible between gabbro and other rock types, except diabase at Site U1309, suggest that gabbro is generally intrusive into more olivine-rich rock types, such as olivine gabbro and troctolite, and in turn intruded by felsic ("leucocratic") dikes and oxide gabbro. These relationships are more common between 400 and 650 mbsf than in the lower part of the hole, where gabbro contacts are commonly more diffuse. The ~140-m-thick interval of olivine-rich troctolite and minor associated lithologic units from 1094 to 1236 mbsf in Hole U1309D forms an integral lithologic package that has been intruded by numerous crosscutting gabbroic dikes of variable thickness at temperatures below the troctolite solidus. Broader-scale contacts with adjacent olivine gabbro appear to be dominantly intrusive and formed under hyper-solidus conditions. Late diabase intrusions are found in several places throughout Holes U1309B and U1309D.

The most abundant rock type recovered is gabbroic in composition and spans a wide range of modal composition, including minor (rarely exceeding a few percent) amounts of olivine, Fe-Ti oxides, and orthopyroxene. Gabbros and gabbronorites exhibit significant variation in grain size (<1 mm to >10 cm), occasionally within a single section of core. Olivine gabbro, the second-most abundant rock type, has highly variable modal compositions on a submeter scale and grades locally into troctolitic gabbro; it is commonly spatially associated with troctolites. A series of olivine-rich rocks (~5% in hole U1309D; dunites, wehrlites, troctolites), grouped as olivine-rich troctolites, are interlayered with gabbroic rocks. In contrast to troctolite, olivine-rich troctolite displays subhedral to rounded medium-grained olivine and interstitial to poikilitic plagioclase and clinopyroxene in variable proportions. These rocks may represent primitive cumulates.

Fe-Ti oxide gabbro, resulting from pervasive, late-magmatic-stage infiltration of evolved melt, composes 7% of the rocks recovered from Hole U1309D. The most common occurrence of oxide concentrations (~80% of the oxide gabbros) is seen as randomly dispersed patches in undeformed, generally coarse-grained gabbro. They are also found as discrete dikelets or layers cutting other rock types with either sharp or diffuse boundaries, and associated with intervals of ductile deformation.

Structure and Alteration

The core from Hole U1309D can be divided structurally into three major units (Fig. 2):

- Structural Unit 1 (0–170 mbsf) is marked by a high but decreasing degree of cataclasis downhole; abundant, late, relatively undeformed diabase; a high degree of greenschist-grade alteration; and a near-present-day orientation of the paleomagnetic inclination. The boundary to structural Unit 2 at ~170 mbsf is marked by a subhorizontal to moderately dipping crystal-plastic shear zone within gabbroic rocks, a high intensity of veining, strong cataclasis, and a ~2-m-thick interval of altered ultramafic rocks.

- Structural Unit 2 (~170 to ~785 mbsf) is marked by a relatively high intensity of veining, including the presence of sulfide minerals. Paleomagnetic inclinations are ~10°–30° shallower than present-day values. The base of structural Unit 2 is defined by a series of greenschist-grade cataclastic fault zones between 695 and 785 mbsf.
- Structural Unit 3 extends beyond 785 mbsf and is characterized by an overall low intensity of cataclastic deformation, veining, and plastic deformation.

Overall, the section is moderately altered at conditions ranging from granulite to zeolite facies and dominated by static, greenschist facies assemblages. Pseudomorphs of igneous textures remain largely unmodified. Magmatic deformation fabrics, as defined by the preferred orientation of plagioclase, were recorded in 22% of the recovered rocks. These fabrics are weak to very weak, except in local intervals, and tend to be developed more clearly in gabbroic rocks with finer initial grain size; foliation is also well developed in the rare layered intervals. In many places, weak crystal-plastic deformation seems to overprint magmatic foliations (Fig. 3). High-strain, crystal-plastic shear zones are rare (Figs. 2 and 3) and are typically restricted to clearly defined, mostly granulite-grade shear zones ranging in width from millimeters to a few meters. This contrasts markedly with the much larger number of high-strain shear zones recorded in the gabbroic complex at ODP Site 735B (Fig. 3A) on the Southwest Indian Ridge (Dick et al., 1999, 2000). Vein intensity in Hole 1309D decreases significantly below 785 mbsf (Fig. 2) and tends to correlate with cataclastic deformation in general and with fault zones on a local scale. On the scale of the entire core, there is no systematic, lithology-dependent distribution of vein type downhole. The amount of strain recorded by brittle fracture and cataclasis is limited overall, except for a few fault zones concentrated in the upper 50 m of Hole U1309D and in discrete intervals downhole, some of which correspond to the boundaries of the defined major structural units, in particular at ~750 mbsf (Fig. 2). Cataclasis is associated locally with oxide gabbro intervals and dikelets, leucocratic veins, and contact zones between diabase intrusions and their gabbroic host rocks.

The lack of significant structures indicative of high displacement by either ductile or brittle processes severely limits the possible thickness of fault zones that could compose a detachment system over the central dome. Poor recovery of the upper 20 m of the footwall allows the possibility that this narrow zone accommodated very high strain along a dominantly brittle fault, as documented at the 15°45'N OCC (MacLeod et al., 2002; Escartín et al., 2003). If so, the fault zone thickness differs from the 50–100 m estimates at the Southern Ridge (Williams et al., 2003; Schroeder and John, 2004; Karson et al., 2006). This difference results either from a decreasing thickness of the fault from the south to the center of the dome or from an overestimated thickness at the Southern Ridge because of limitations in accurately determining the structural depth of submersible samples. Extensive amphibolite facies deformation is lacking, and high-strain ductile shear zones are rare. The absence of a thick zone of high-temperature ductile deformation in the footwall and the apparent tectonic history (less rotation in the upper 180 m and variable rotations between several distinct, few-hundred-meter sections downhole, Fig. 2) suggested by paleomagnetic inclination measurements indicate complexity in structural evolution that differs from a simple model of a deep-rooted detachment fault, predicted to be associated with high-temperature deformation, and with constant or monotonically varying footwall rotation with depth.

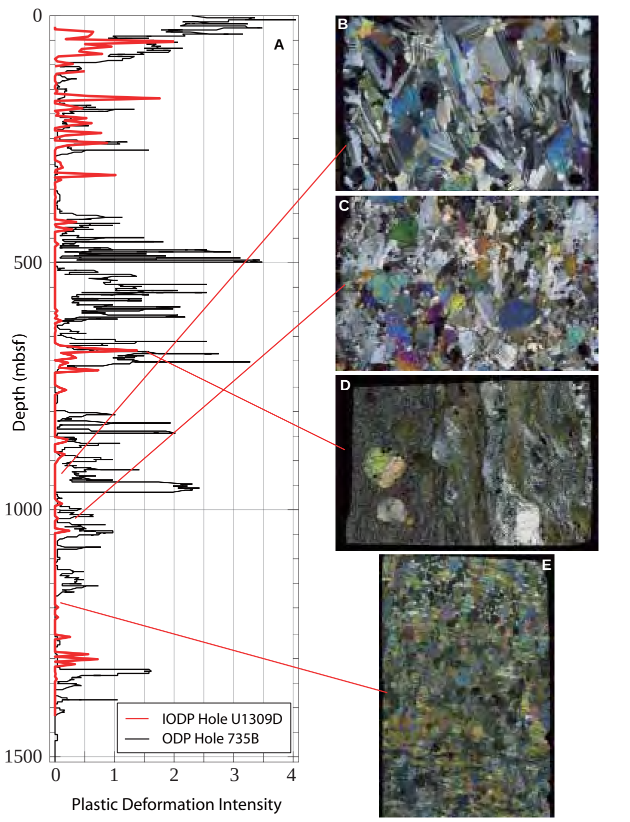

Figure 3. Intensity of crystal-plastic deformation and microstructural characters of magmatic and plastic foliations (cross-polarized light, field of view ~2 cm). [A] Compared deformation intensities (5 m running average) in ODP Hole 735B and IODP Hole U1309D (Crystal-plastic deformation scale : 0 = undeformed, 1 = weakly foliated, 2 = strongly foliated, 4 porphyroclastic). [B] Magmatic foliation. [C] High-temperature, low-stress, crystal-plastic foliation. Note the dynamic recrystallization of plagioclase and olivine. Crystal-plastic strain probably overprints a pre-existing magmatic foliation. [D] Mylonitic foliation (low temperature, high stress) with relict plagioclase and clinopyroxene porphyroclasts. [E] Olivine-rich troctolite with alignment, possibly magmatic, of weakly elongated olivines. Note that poikilitic plagioclase and clinopyroxene grains are not elongated parallel to foliation.

Altered mineral assemblages in rocks from Site U1309 record cooling of mafic plutonic rocks from submagmatic conditions (>1000°C) to zeolite facies temperatures (<200°C) during the unroofing and uplift of the Atlantis Massif. Individual samples generally display a range of superimposed metamorphic conditions, but no single sample records the entire cooling history of the site. Overall, alteration intensity is moderate, tends to decrease downhole, and is commonly related to vein intensity (Fig. 2). Local exceptions to this general downhole decrease in alteration intensity often correlate with an increase in modal abundance of olivine. Coarser-grained gabbro intervals are generally more altered than medium- to coarse-grained units. Intervals of olivine-rich troctolite show alteration restricted to heterogeneous serpentine networks, with strong alteration gradients from the contact with intensely veined intercalated gabbros to fresher cores. The latter contain local intervals of very fresh (as low as 1% serpentinization) olivine-rich (as much as >90%) rocks.

The metamorphic and alteration history recorded at Site U1309 is summarized as follows:

1. High-temperature, near-solidus, mylonitic deformation and recrystallization at granulite- to upper-amphibolite-facies conditions.

2. A widespread, largely static upper-greenschist-facies to lower-amphibolite-facies event (Figs. 2 and 4). The upper ~380 m of the core shows a beautiful alteration profile with evidence for pervasive static infiltration of seawater with decreasing temperature. In addition, these same rocks show localized alteration superimposed in some cases on pervasive alteration, presumably reflecting localized fluid flow and metasomatism. Below this depth, alteration is generally restricted to halos around veins, fractures, and igneous contacts.

3. Static, lower greenschist to subgreenschist metamorphism. Serpentinization above ~300 mbsf is restricted to rocks where olivine was in excess over plagioclase and was therefore still present after the corona-forming reaction between olivine and plagioclase (stage 2) went to completion. At deeper levels, serpentine, prehnite, and hydrogrossular are often localized on closely spaced, variably oriented fractures.

Correlations Between Alteration and Geophysical Signature

Downhole logging and physical property measurements on core samples do not correlate strongly with rock type (Fig. 2). Instead, alteration may play a stronger role in determining the geophysical signature of the upper 1.5 km of the central dome. Average sample density varies only slightly, from 2.800 g·cm^{-3} in the upper 380 mbsf to 2.900 g·cm^{-3} in the lower ~1 km (Fig. 2). Meter-scale intervals show more variability in both sample and logging measurements, with oxide gabbro sometimes reaching >3.200 g·cm^{-3} and highly altered olivine-rich zones dropping to <2.700 g·cm^{-3}. Average compressional velocity is 5.6 km·s^{-1} in the upper ~400 m and 5.8 km·s^{-1} for the interval ~500–800 mbsf. The mid-expedition checkshot experiment extended to 840 mbsf, the base of the hole at that stage. Instrument failure and poor weather

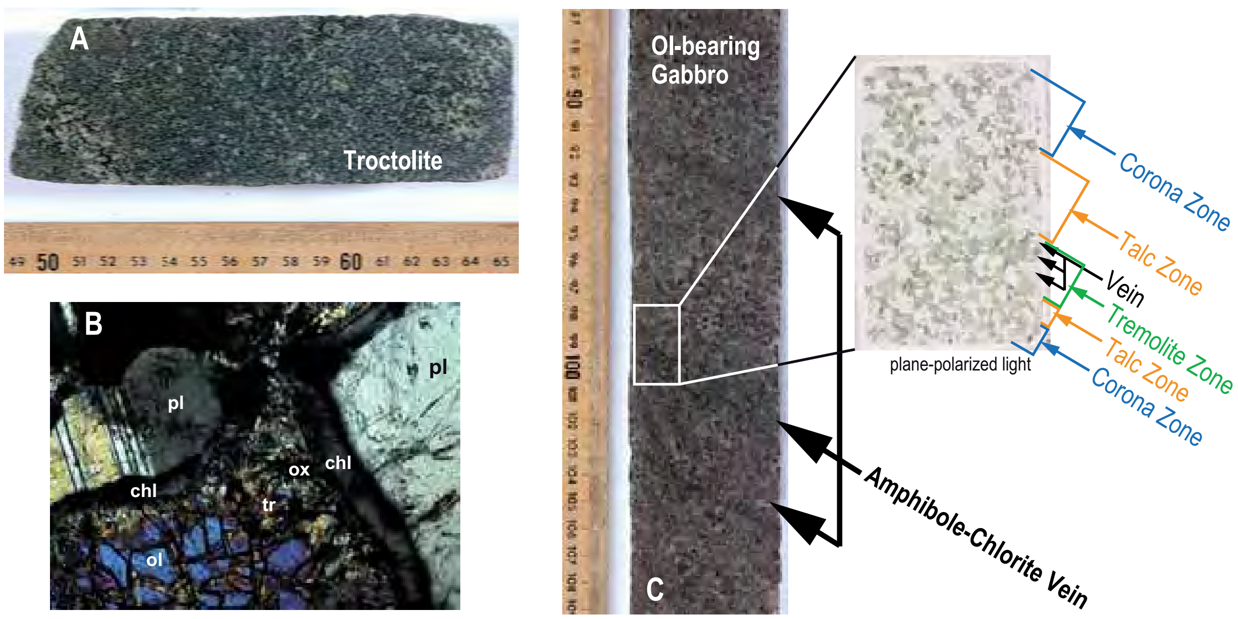

Figure 4. Most common alteration patterns. [A] Corona mesh texture in troctolite layer (Hole U1309B, ~77 mbsf). [B] Thin-section photomicrograph of a corona texture in olivine gabbro consisting of talc, tremolite, oxides after olivine, and chlorite after plagioclase where the two original minerals were in contact (Hole U1309D, ~403 mbsf, cross-polarized light, field of view ~1.4 mm). [C] Example of alteration halo around chlorite-amphibole-rich veins (Hole U1309D, ~941 mbsf).

precluded acquisition of seismic data in the final logging run. Seismic velocity values obtained by sample and sonic log measurements range from ~5.1 to 6.8 km·s^{-1}. Values less than 5.5 km·s^{-1} are common in the upper 180 mbsf and in the olivine-rich interval ~280–380 mbsf, below which values near 6 km·s^{-1} are most common. Only thin intervals have a velocity greater than 6.5 km·s^{-1} corresponding to olivine gabbro or olivine-rich troctolite units with little alteration.

Shipboard processing of the checkshot data revealed only first-arrival information. Although the signal-to-noise ratio was generally good for the stacked data, considerable noise was present due to impacts of the pipe in the upper part of the hole. After the expedition, individual traces were analyzed, and particularly noisy records were removed prior to re-stacking and bandpass filtering (5–120 Hz). The processed data (Fig. 5) show a secondary arrival that trails the first peak by a time that decreases from 41 ms to essentially zero between stations at 275 and 435 mbsf. Using the delays at the 275 and 345 mbsf stations and a velocity of 5.5 km·s^{-1}, a reflector at ~390 mbsf could produce the secondary arrival that also corresponds to a strong reflector on the MCS line closest to Hole U1309D. It is likely that this represents the D reflector in this part of the dome.

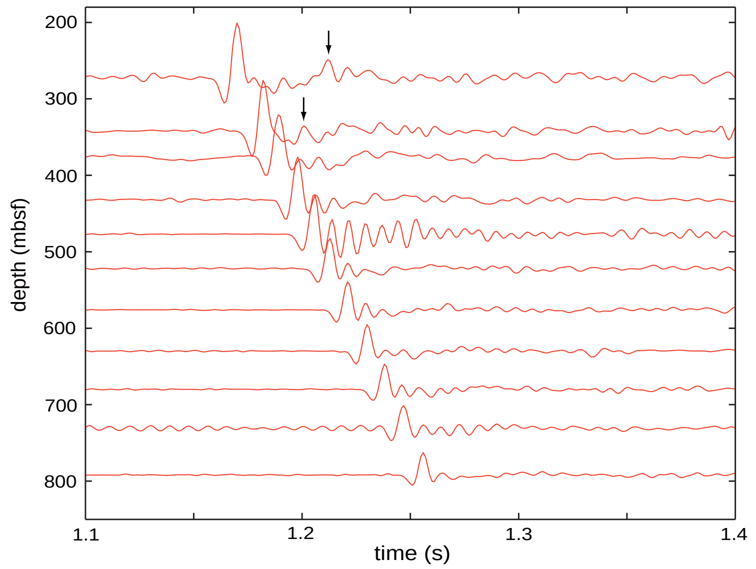

Figure 5. Filtered waveforms for checkshot experiment in upper part of Hole U1309D. Main arrival has strong signal-to-noise ratio. Removal of especially noisy traces brings out character of later arrivals. At upper stations, a secondary arrival (arrows) probably corresponds to D reflector of Canales et al., (2004).

The temperature-acceleration-pressure (TAP) tool recorded a temperature of 120°C at the bottom of the hole (Fig. 6). Temperature increased with depth as expected but was somewhat lower than predicted from a simple cooling-plate model of a spreading ridge flank with an age of ~2 Ma. The measured temperatures are a minimum estimate, however, because of hole cooling during coring. These initial results suggest that thermally driven flow is likely to occur in the hole. Several drops of a few degrees were recorded in narrow intervals (two of which coincide with documented fault zones at ~750 and 1110 mbsf) on repeated TAP runs (Fig. 6), perhaps indicating localized fluid flow.

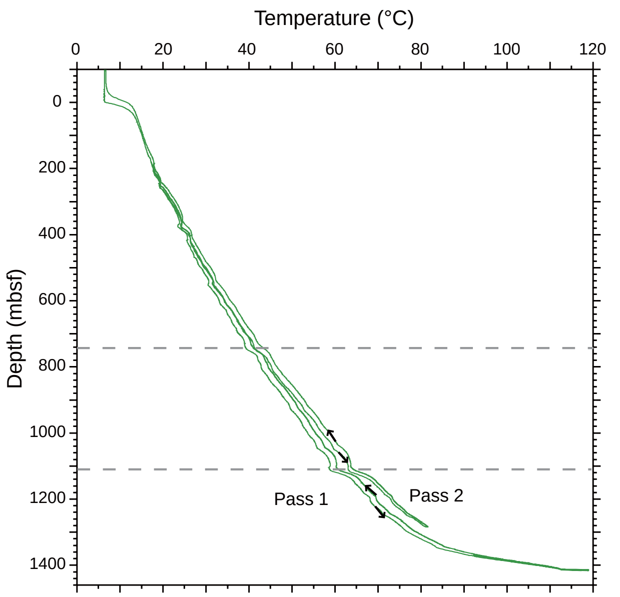

Figure 6. Temperature recorded by TAP tool. Increase in borehole temperature with time is recorded during downhole and uphole logging runs and during repeated logging passes. Dashed lines indicate recognized fault zones (see Fig. 2) which coincide with local dips in temperature.

Concluding Remarks

Igneous rocks recovered at Site U1309 provide an exceptional record of magmatic accretion, tectonic exposure, and hydrothermal alteration in a slow-spreading ridge environment. The exposures of peridotite along the southern wall of the Atlantis Massif, the geophysical results suggesting that at least portions of the dome contain fresh olivine-rich rock (possibly olivine-rich troctolites), and the downhole variability at Site U1309 all likely indicate significant lateral lithological heterogeneity over distances as short as hundreds of meters across the footwall.

The Atlantis Massif is the fourth location where drilling an OCC (i.e., a corrugated massif, or an inside corner high capped by fault rocks) at a slow-spreading ridge has been attempted by ODP or IODP. A total of fourteen holes (>10 m deep) were cored at seven different sites in three different OCCs during ODP Legs 118, 153, 176, 179, and 209 (Robinson, et al., 1989; Cannat, et al., 1995; Dick, et al., 1999; Pettigrew et al., 1999; Kelemen, et al., 2004). Those efforts recovered only gabbroic sections, ranging from Fe-Ti oxide gabbros to troctolites, locally intruded by diabase. The latest result s of IODP Expeditions 304 and 305 point to the need for a new paradigm of crustal accretion in regions that are classically inferred to be representative of magma-starved portions of the ridge. One possible working model relates the development of OCCs to the occurrence of periodically larger gabbroic bodies beneath slow-spreading ridge segment ends (Ildefonse et al., 2006). Uplift and exhumation of these gabbroic bodies would be enabled by deformation that localized predominantly within the serpentinized peridotite that initially surrounded them. The northward extension, inside the core of the Atlantis Massif, of the serpentinites outcropping at the southern wall is presently unknown. These serpentinites could represent a relatively thin sheet of mantle rocks surrounding a dominantly gabbroic core. Alternatively, a significant, but unknown part of the Atlantis Massif footwall may be composed primarily of serpentinite and peridotite. Further IODP operations in this region should combine deeper drilling in Hole U1309D and drilling the southeast shoulder of the Atlantis Massif.

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IODP Expeditions 304 and 305 Scientists

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Rapid Sedimentation, Overpressure, and Focused Fluid Flow, Gulf of Mexico Continental Margin

by Jan H. Behrmann, Peter B. Flemings, Cédric M. John, and the IODP Expedition 308 Scientists

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Abstract

Expedition 308 of the Integrated Ocean Drilling Program (IODP) was the first phase of a two-component project dedicated to studying overpressure and fluid flow on the continental slope of the Gulf of Mexico. We examined how sedimentation, overpressure, fluid flow, and deformation are coupled in a passive margin setting and investigated how extremely rapid deposition of fine-grained mud might lead to a rapid build-up of pore pressure in excess of hydrostatic (overpressure), underconsolidation, and sedimentary mass wasting. Our tests within the Ursa region, where sediment accumulated rapidly in the late Pleistocene, included the first-ever *in situ* measurements of how physical properties, pressure, temperature, and pore fluid compositions vary within low-permeability mudstones that overlie a permeable, overpressured aquifer, and we documented severe overpressure in the mudstones overlying the aquifer. We also drilled and logged three references sites in the Brazos-Trinity Basin IV and documented hydrostatic pressure conditions and normal consolidation. Post-expedition studies will address how the generation and timing of overpressure control slope stability, seafloor seeps, and large-scale crustal fluid flow. The operations of Expedition 308 provide a foundation for future long-term *in situ* monitoring experiments in the aquifer and bounding mudstones.

Introduction

Rapid sedimentation at rates >1 mm·yr^{-1} generate overpressure in many sedimentary basins around the world (Rubey and Hubbert, 1959; Fertl, 1976). When low-permeability sediments are rapidly loaded, pore fluids cannot escape, and the fluids bear some of the overlying sediment load. In this situation a pore pressure exceeding the hydrostatic pressure (overpressure, P*) develops. Recent work has focused on the coupling of rapid sedimentation and stratigraphic architecture to produce two- and three-dimensional flow fields. If, for example, permeable sand is rapidly buried by low-permeability mud of laterally varying thickness (Fig. 1), fluids flow sub-horizontally through the sand layer to regions of thin overburden before they are expelled into the overlying sediment. This creates characteristic distributions of sediment properties, fluid pressure, effective stress, temperature, and fluid chemistry in the aquifers and the bounding mud (Fig. 1). This simple flow-focusing process can cause slope instability near the seafloor (Dugan and Flemings, 2000; Flemings et al., 2002). In the deeper subsurface, overpressures created by focused flow can drive fluids through low-permeability strata to vent

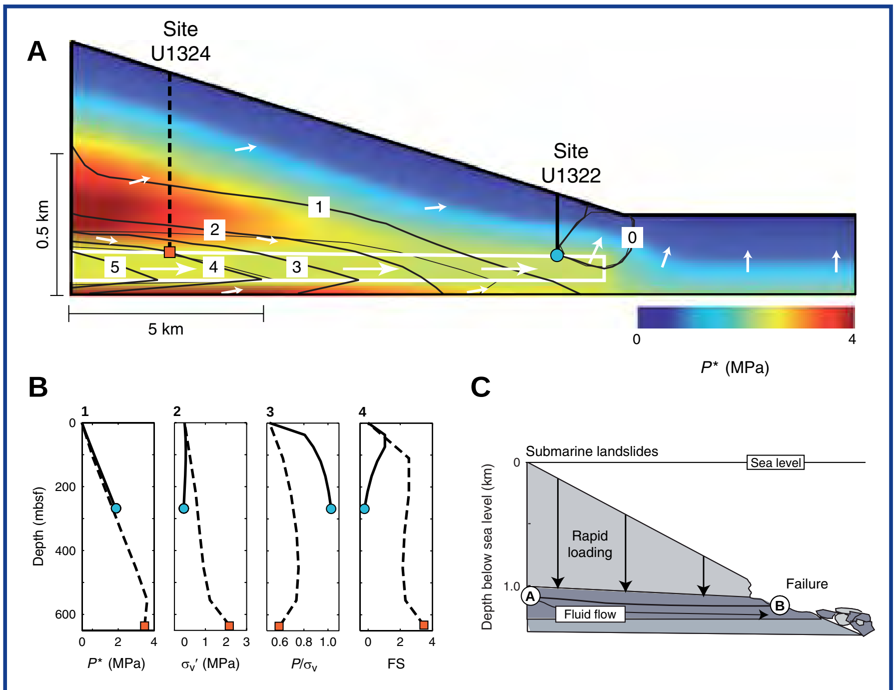

Figure 1. Flow-focusing model approximating conditions in Ursa Basin. [A] Low permeability sediments are rapidly deposited on a high permeability aquifer (outlined in white). Sedimentation rate decreases from left to right, resulting in final wedge-shaped geometry. Rapid sedimentation generates overpressure (P*; color contours) that is greatest on the left (red) side of the picture. Flow is driven laterally (left to right) along the aquifer and is expelled at the toe of the slope where the aquifer ends (white arrows). Vertical effective stress (black contours) is lowest on the right side of the picture. [B] Predicted overpressure profiles where overburden is thick (Site U1324) and thin (Site U1322). (1) Overpressure at Site U1322 is slightly greater than at Site U1324 for equivalent depths. (2) Vertical effective stress (σ_v') is much lower at Site U1322 than at Site U1324. (3) Pore pressures (P) equal overburden stress (σ_v) at Site U1322. (4) Slope failure is predicted by infinite slope analysis near Site U1322 for FS < 1. FS relates failure-driving stress to available shear strength for shallow failures. [C] Model parameters: low permeability mudstone $k_v < 5 \times 10^{-8}$ m^2 and $k_h < 5 \times 10^{-16}$ m^2; aquifer permeability $k_h = k_v\ 5 \times 10^{-14}$ m^2; maximum sedimentation rate = 3.5 mm·y^{-1}; minimum sedimentation rate = 0.8 mm·y^{-1}. [C] Drawing of how flow focusing drives slope instability.

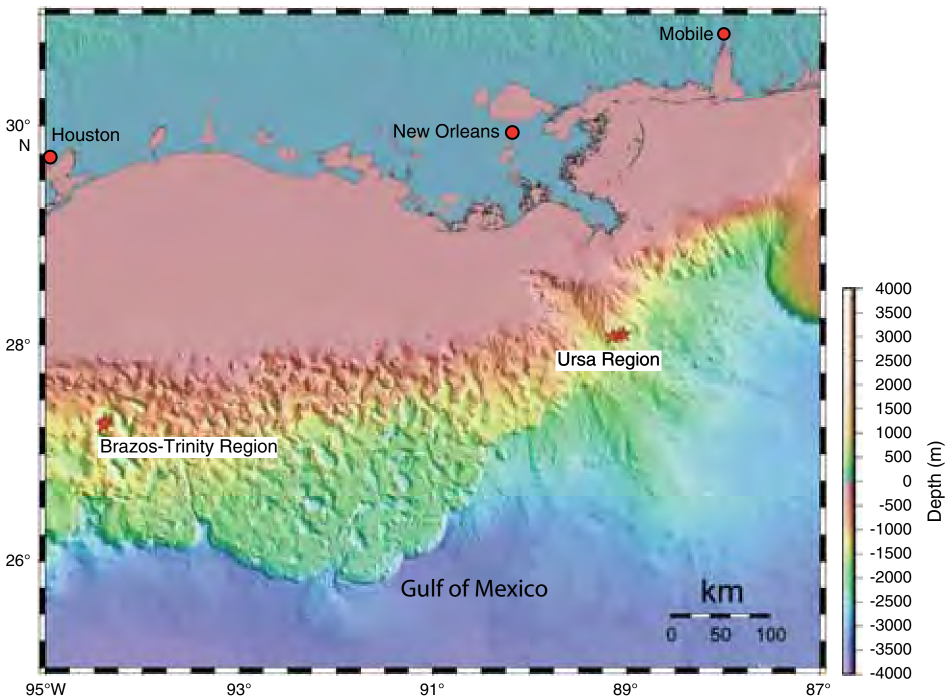

Figure 2. Bathymetric image of continental slope of Gulf of Mexico. Drilling took place in Brazos-Trinity (reference sites) and Ursa (overpressured sites) regions.

ultimately at the seafloor (Boehm and Moore, 2002; Davies et al., 2002; Seldon and Flemings, 2005). This is a potentially important mechanism for the transfer of fluids from the solid earth to the hydrosphere and the atmosphere.

Brazos-Trinity Reference Sites

Brazos-Trinity Basin IV is located 200 km due south of Galveston, Texas (U.S.A.) in ~1400 m of water (Fig. 2). As one of a chain of five basins that are separated by interbasinal highs, it is a classic area for analysis of turbidite depositional environments, and it is a modern analog to describe the formation of deep-water turbidite reservoir deposits (e.g., Badalini et al., 2000; Winker, 1996; Winker and Booth, 2000). The primary data used to evaluate the borehole locations comprise a high-resolution, two-dimensional (2-D) seismic survey conducted by Shell Exploration and Production Company to image the turbidite stratigraphy. The three drilling sites are shown on dip seismic Line 3020 (Fig. 3). Site U1320 is located where the turbidite deposits are thickest, whereas Site U1319 lies along the southern flank of Basin IV where turbidite deposits are more condensed. Site U1321 was a logging-while-drilling and measurement-while-drilling (LWD/MWD) site and was not cored. This is the first time in the history of scientific ocean drilling that a hole was drilled exclusively for logging purposes.

Integration of core, downhole measurement, and seismic data enabled a detailed lithostratigraphic (Fig. 4) and physico-chemical characterization of the basin and dating of key surfaces. The data provide the basis to estimate sediment fluxes over time across a source-to-sink system. A 175-m-thick sequence of sand-rich turbidite fans, mass-transport deposits, and hemipelagic sediment has accumulated within the last ~120,000 years in Brazos Trinity Basin IV. Pre-fan deposits form a conformable sequence dominated by terrigenous clays transported by dilute turbidity currents and river plumes. The two sequences are separated by a thin (~1 m) layer of microfossil-rich clay, interpreted to represent the sea-level highstand during Marine Isotope Stage 5e. The basin infill is marked by two main pulses of mass-gravity flow deposition, separated by a pause in turbidity current activity. The pause lasted as much as 45 ky, starting at ~90 ka. The microfossil-rich clays in this interval contain the Los Chocoyos ash layer (Y8), a physical correlation marker across Basin IV and adjacent basins. The lower part of the basin contains mostly thin-bedded, muddy turbidites. The upper part contains muddy slump deposits derived from the basin margin and sand-rich turbidites that form several packets of very fine to fine sand beds that are

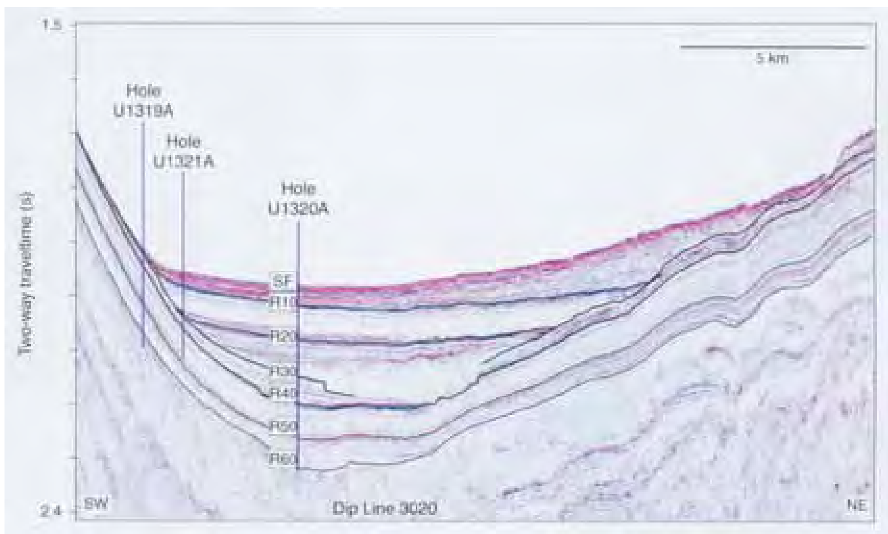

Figure 3. Reflection seismic section (Dip Line 3020) across Brazos Trinity Basin IV. Specific drill sites are located at cross-tie with strike Line 3045 (Site U1320), strike Line 3055 (Site U1321), and at southern limit of this line (Site U1319). R10–R60 = major seismic reflectors correlatable between drill holes. SF = seafloor.

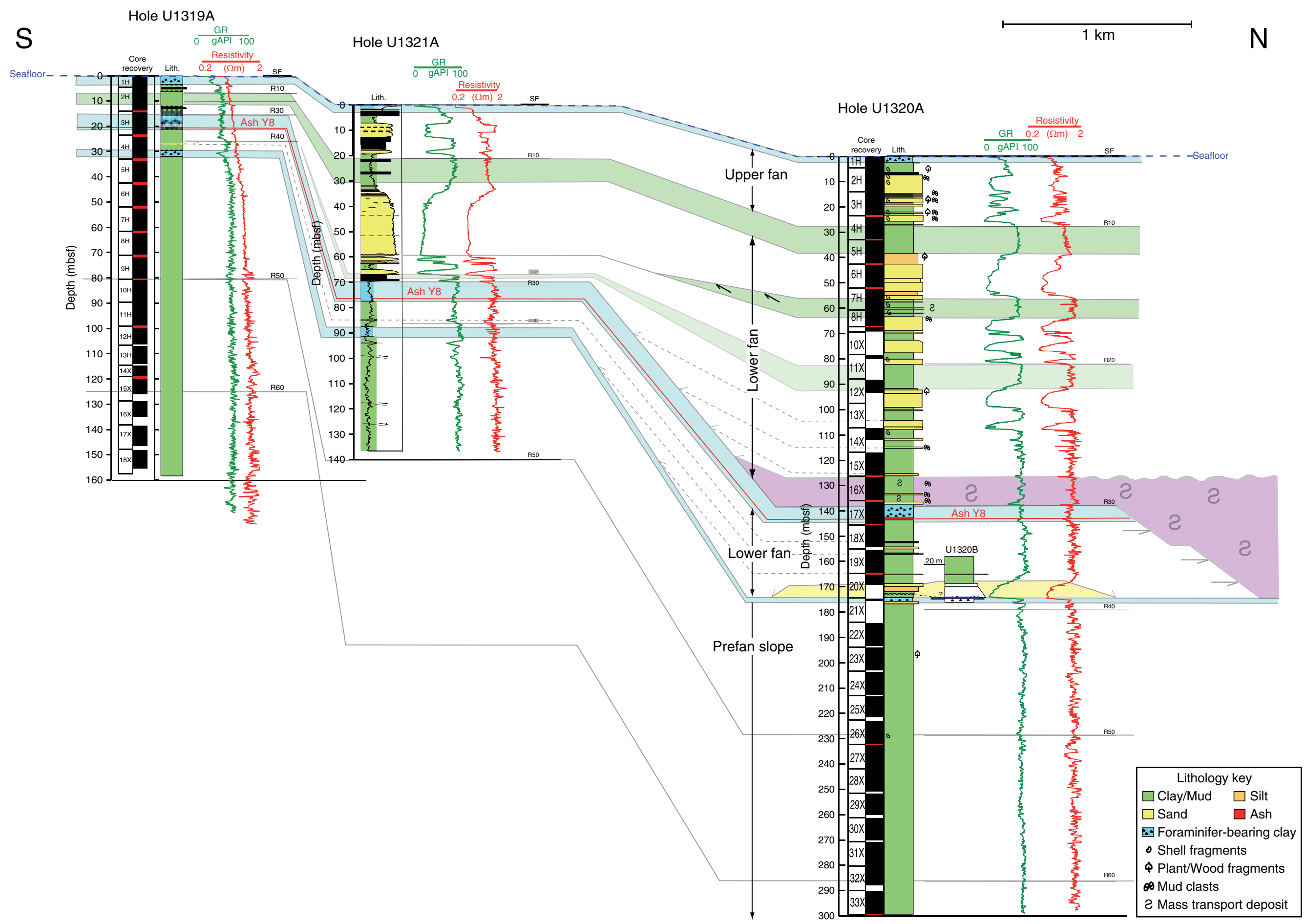

Figure 4. Stratigraphic cross-section of Brazos-Trinity Basin IV. Data of core and well logs are at sea level. Stratigraphic ties between sites are based on seismic, lithology, log signature, and biostratigraphy. Each column contains depth scale, schematic lithology, gamma ray (GR) and resistivity logs (from LWD data), and depth of key seismic surfaces. In core recovery diagram, black = cored, red = overlap due to core expansion, and white = no recovery. mbsf = meters below sea floor.

5–25 m thick (Fig. 4). Rates of basin subsidence, sea-level change, and average sediment accumulation or erosion are of similar magnitude in this system, resulting in a complex interaction between (a) sea level changes and deltaic dynamics, which affect the delivery of sediment in the source area, (b) salt tectonics, which affects the basin configuration and topographic gradients over time, and (c) the dynamic interaction between turbidity currents and the underlying topography.

The three drilling sites in the Brazos-Trinity Basin IV provided evidence of progressive and punctual downhole changes in physical properties as measured onboard the *JOIDES Resolution*, especially at Site U1319. Basin in-fill sediments (down to reflector R40) and underlying hemipelagic drape sediments (below reflector R40) are essentially non-slumped, normally consolidated muds that provide an excellent reference for materials found within the basin (Site U1320) and at Ursa Basin (Sites U1322 and U1324). The sediment porosity at Site U1319 decreases exponentially downhole from 80% to 50%. In comparison, Site U1320 has a section of underconsolidated muds and clays below Reflector R40; this was not anticipated but is explained by rapid sediment loading precluding fluid drainage and consolidation of muds of the basin interior.

Overpressured Ursa Basin Sites

Ursa Basin lies approximately 150 km south-southeast of New Orleans, Louisiana (U.S.A.) in ~1000 m of water (Fig. 2). The region is of economic interest because of its prolific oilfields that lie >4000 meters below the seafloor (mbsf; e.g. Mahaffie, 1994). We were interested in the sediments from 0 to 1000 mbsf (e.g., Pratson and Ryan, 1994; Pulham, 1993). Four three-dimensional (3-D) seismic data sets were used to constrain stratigraphy within Ursa Basin. The high-resolution surveys were conducted by Shell Exploration and Production Company for the purpose of shallow hazards analysis. Figure 5 shows the seismic transect along which Sites U1322, U1323, and U1324 were drilled. The sand-dominated Mississippi Canyon Blue Unit (Fig. 5) is a late-Pleistocene "ponded fan" deposited in a broad topographic low. The Blue Unit is overlain by a mud-dominated levee-channel assemblage. The most spectacular feature is the

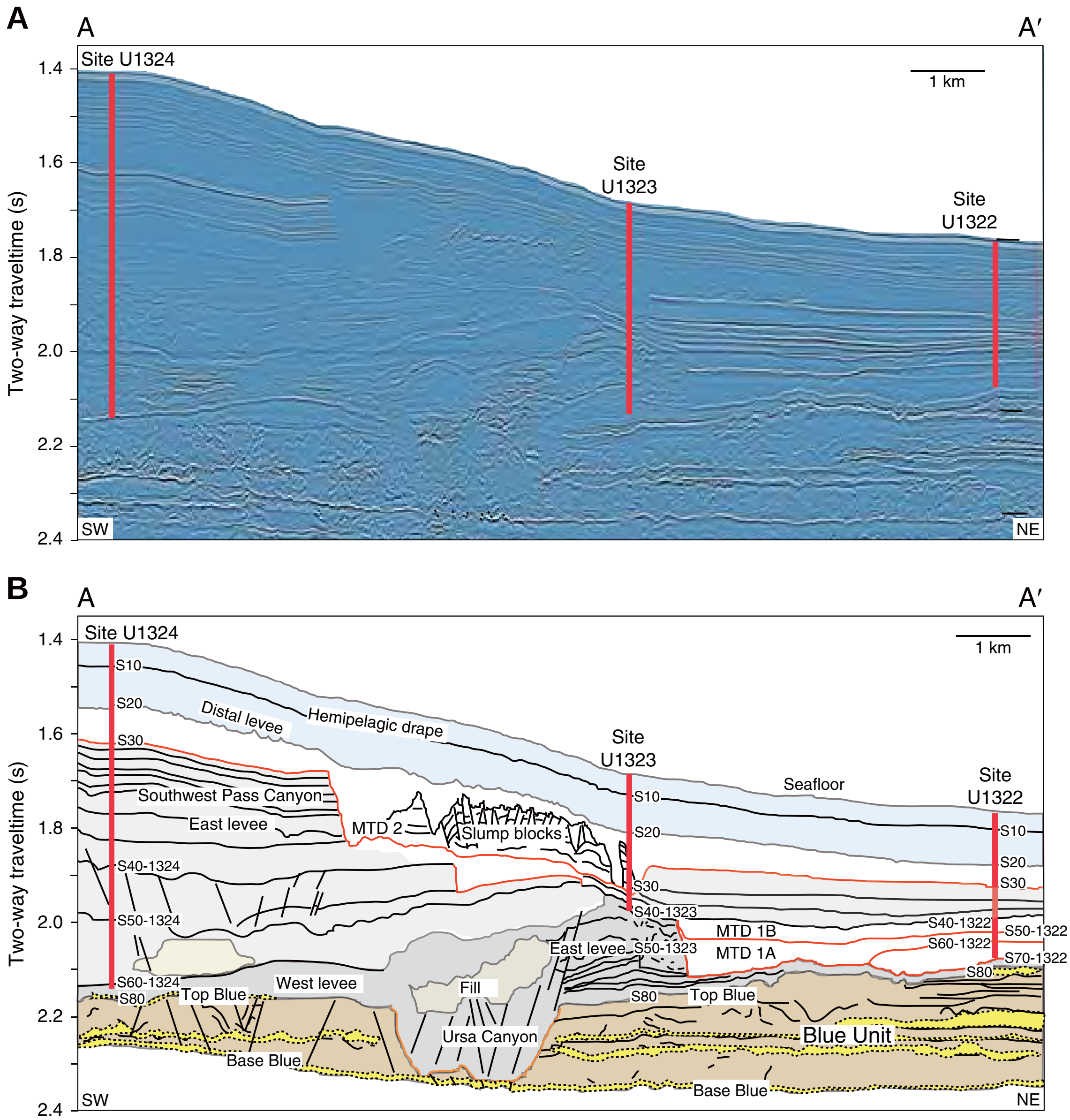

Figure 5. [A] Seismic cross-section A–A' from Ursa Basin. [B] Interpreted cross-section A–A'. Sand-prone Blue Unit has been incised by channel-levee complex and then overlain by thick and heavily slumped hemipelagic mudstone wedge that thickens westward (left). Blue Unit sands correlate to distinct seismic facies. Thickness of hemipelagic mudstone above Blue Unit does not change significantly in north-south direction. Seismic reproduced with permission of Shell Exploration and Production Company.

sand-cored levee-channel of the Ursa Canyon, overlain by the muddy eastern levee deposits of the Southwest Pass Canyon and a hemipelagic drape cover. The mudstone package lying above the Blue Unit has numerous detachment surfaces that record slumping and mass transport deposits.

The Ursa Basin sites provided a west-east transect that tested the flow-focusing model of differential loading on a permeable aquifer. Overburden was drilled and sampled to 608 m depth at Site U1324 (thick overburden) and to 234 m at Site U1322 (thin overburden). We used a penetrometer (Fig. 6) to measure overpressure below 100 m at both sites. Normalized overpressure of approximately 0.6 was determined at the base of each site (i.e., the pore pressure lies 60% of the way between hydrostatic pressure and lithostatic pressure). The temperature gradient is 18°C·km^{-1} at Site U1324 and 26°C·km^{-1} at Site U1322. Thermal conductivities at the two locations are similar (1.15–1.2 W·m^{-1}·K^{-1}), implying a vertical conductive heat flow of ~22 mW·m^{-2} at Site U1324 versus ~30 mW·m^{-2} at Site U1322.

Sedimentation has accumulated more rapidly at Site U1324 (10 mm·y^{-1}) than at Site U1322 (3.8 mm·y^{-1}). In spite of the almost three-fold difference in sedimentation rate, the similar overpressure gradients present at these two sites imply a component of lateral flow between them. This lateral flow drives fluids from Site U1324 toward Site U1322, increases the pressure at Site U1322 relative to a system with only vertical fluid migration, and decreases pressure at Site U1324 relative to a system with only vertical migration. The

Blue Unit, composed of interbedded sheet sands and mudstones, is interpreted to facilitate the lateral transfer of fluids from Site U1324 to Site U1322, making the regional pressure field diverge from a simple one-dimensional, compaction system. Core, log, and seismic interpretations document numerous scales of slumping, faulting, and soft-sediment deformation with increased occurrence at Site U1322. This deformation is consistent with predictions of the flow-focusing model. The dramatic difference in sedimentation rates between the sites also helps to explain the difference in observed thermal gradients. These results suggest that at the basin scale, this type of lateral fluid flow may be the prime factor for the distribution and occurrence of cold seeps, mud volcanoes, and repeated submarine landslides generating major mass transport deposits.

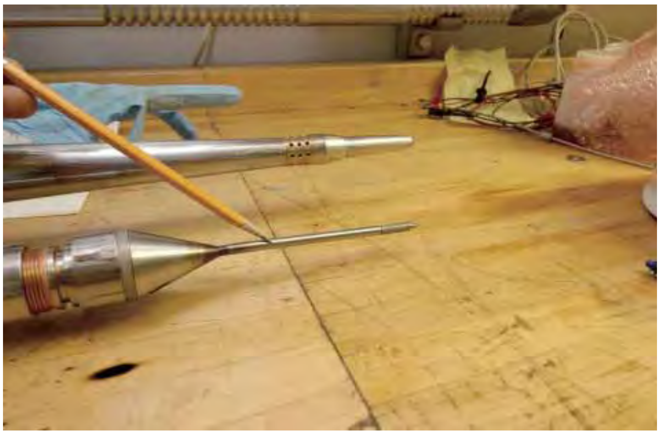

Figure 6. Temperature Two Pressure probe (T2P, foreground) and Davis-Villinger Temperature-Pressure Probe (DVTPP, background). Both tools measure formation pressure by being forced into formation by drill string.

Expectations and Achievements of IODP Expedition 308

A fundamental achievement of IODP Expedition 308 is that the overpressure profile as a function of depth at Sites U1322 and U1324 in Ursa Basin could be directly measured. These measurements were difficult, and we experienced a high rate of failure; however, we ultimately acquired enough data to constrain the overpressure field above the Blue Unit. Preliminary interpretations suggest that flow focusing is occurring in this basin and contributing to deformation and failure of sediments where overburden is thin. This is the first time in the history of scientific ocean drilling that the spatial variation of the pressure field has been documented at such resolution. We also acquired an extraordinary data set documenting a striking difference in temperature gradients between Sites U1322 and U1324.

We wanted to establish reference logging and core properties where overpressure is not present at a range of effective stresses in Brazos-Trinity Basin IV. Coring and logging were successful at all locations there, resulting in a high-resolution recontruction of basin architecture and lithostratigraphy, in part below the level of individual lithostratigraphic subunits.

Our data on pore pressure, sediment properties, and overburden stress (Fig. 7) will provide a basis to assess the potential for slope failure, especially in Ursa Basin, and to estimate the conditions that drove previous slope failures. A major component of the ongoing post-expedition research is the integration of the stratigraphic geometry, physical properties, timing, and pressures associated with these mass-wasting processes.

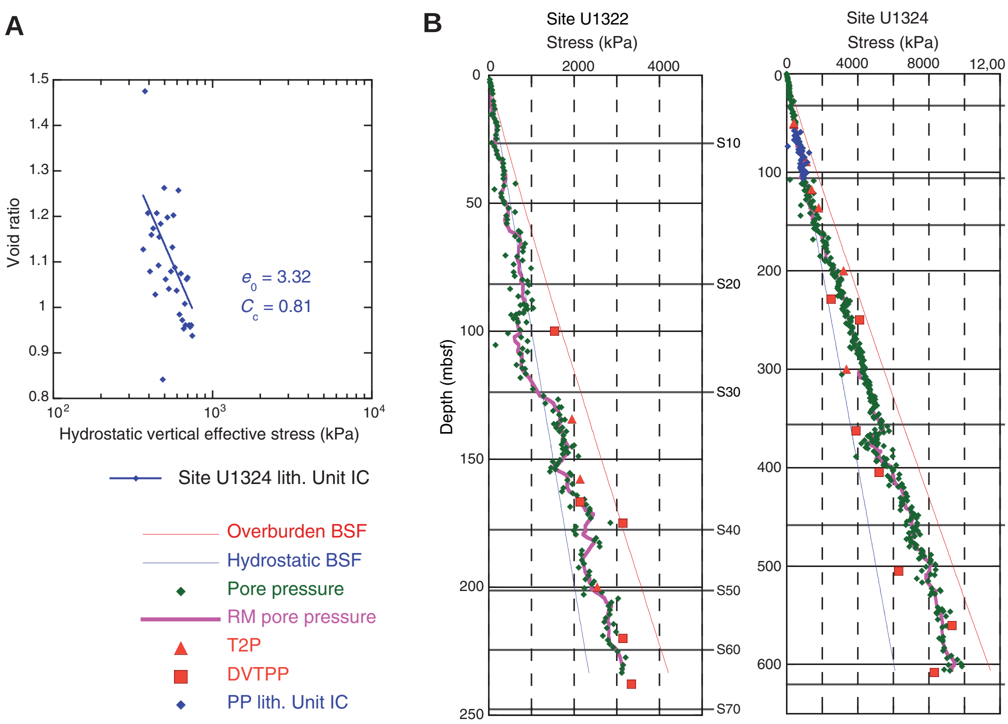

Figure 7. [A] Void ratio (e) versus hydrostatic vertical effective stress (σ_{vh}) for lithostratigraphic Subunit IC at Site U1324. Reference void ratio (e_0) and compression index (C_c) are derived from fit of type $e = e_0 - C_c \ln(\sigma_{vh})$. [B] Pore pressures for Site U1322 and U1324 are derived from parameters derived in [A] assuming that lithostratigraphic Subunit IC (blue dots) at Site U1324 is hydrostatically pressured. Pore pressures recorded at end of temperature and dual pressure probe (T2P) (red triangles) and DVTPP (red squares) deployments are also shown. BSF = below seafloor, RM = running mean, PP = pore pressure.

IODP Expedition 308 monitored downhole pressure and lithology in real time using the MWD approach and for the first time used weighted mud as a tool to drill and core overpressured regimes. Real-time monitoring allowed us to observe shallow-water flow and to respond to this incident by raising the mud weight to retard flow into the borehole, thereby proving the feasibility of this technique for long-term, *in situ* monitoring experiments in the aquifer and bounding mudstones.

Data from the ponded turbidite system in Brazos Trinity Basin IV and the channelized systems present in Ursa Basin are of great interest for further studies by academic and industry researchers. They will likely break new ground, especially in the field of geotechnical and hydrogeological analysis of continental slopes along passive and active continental margins. We have also shown that *in situ* measurements of pore pressure in fine-grained sediments can be performed with overall success and that drilling into overpressured formations with riserless technology can be managed using heavy mud. Future drilling in a variety of settings might benefit from the controlled use of weighted mud to stabilize the borehole.

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Stages of Gas-Hydrate Evolution on the Northern Cascadia Margin

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and the IODP Expedition 311 Scientists

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Introduction

Natural gas hydrate occurs beneath many continental slopes and in arctic permafrost areas. Recent studies have indicated that the largest deposits of gas hydrate might lie in nearly horizontal layers several hundred meters beneath the seafloor of continental slopes, especially in the large, accretionary sedimentary prisms of subduction zones. Expedition 311 of the Integrated Ocean Drilling Program (IODP) investigated the formation of gas hydrate in the accretionary prism of the Cascadia subduction zone (Fig. 1). The primary objectives of Expedition 311 were to test and constrain geological models of gas hydrate formation by upward fluid and methane transport in accretionary prisms. We specifically sought to (a) determine the mechanisms that control the nature, magnitude, and distribution of the gas hydrate, (b) find the pathways of the fluid migration required to form large concentrations of gas hydrate, (c) examine the effects of gas hydrate on the physical properties of the host sediment, and (d) investigate the microbiology and geochemistry associated with the occurrence of gas hydrate. Furthermore, we concentrated on the contrast between methane transport by focused flow in fault zones and by dispersed pervasive upward flow at various scales of permeability.

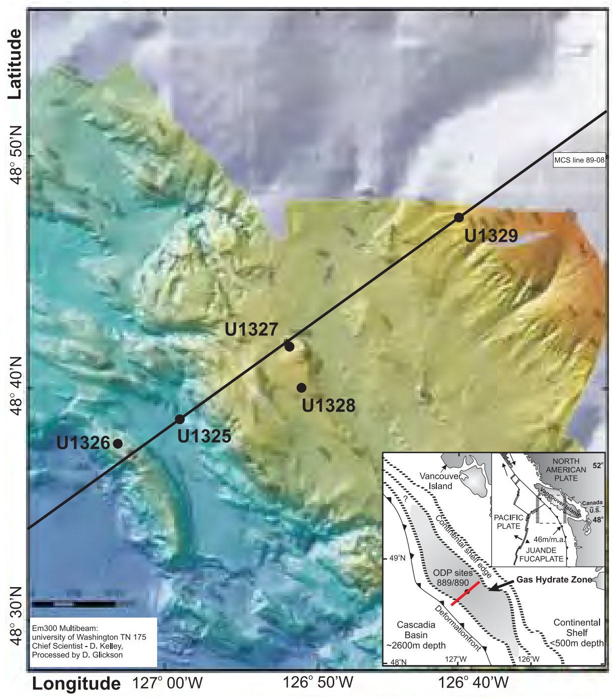

Figure 1. Multibeam bathymetry map along transect across accretionary prism offshore Vancouver Island established during IODP Expedition 311 (courtesy of D. Kelly and J. Delaney, University of Washington and C. Barnes, C. Katnick, NEPTUNE Canada, University of Victoria). Inset: General tectonic location of drilling transect near previous ODP Sites 889 and 890. BSR is present on ~50% of mid-continental slope (shaded area, from Hyndman et al., 2001).

Background

Along the northern Cascadia margin, the Juan de Fuca plate converges nearly orthogonally to the North American plate at a present rate of ~45 mm·y^{-1} (e.g., Riddihough, 1984). Seaward of the deformation front, the Cascadia Basin consists of pre-Pleistocene hemipelagic sediments overlain by rapidly deposited Pleistocene turbidites for a total sediment thickness of ~2500 m. Most of the incoming sediment is scraped off the oceanic crust and folded and thrust upward to form elongated anticlinal ridges that reach as high as 700 m above the adjacent basins.

A general model for forming gas hydrate by removal of methane from upwardly expelled fluids was proposed for the study area (Hyndman and Davis, 1992). Mainly microbial methane, inferred to be produced over a thick sediment section, migrates vertically and forms gas hydrate when it enters the stability field. The highest concentration of gas-hydrate is predicted to occur just above the bottom-simulating reflector (BSR). A model has also been proposed for how free gas and the resulting BSR will form as the base of gas hydrate stability moves upward as a result of post-Pleistocene seafloor warming, uplift, and sediment deposition (e.g., Paull and Ussler, 1997; von Huene and Pecher, 1998). In addition, physical and mathematical models have been developed for the formation of gas hydrate from upward methane advection and diffusion (e.g., Xu and Ruppel, 1999).

Recently, evidence has been identified for focused fluid or gas flow and gas-hydrate formation on the Vancouver margin. The most studied site is an active cold-vent field associated with near-surface gas-hydrate occurrences (e.g., Riedel et al., 2002) and with fault-related conduits for focused fluid or gas migration. It is unknown how important these cold vents are in the total budget of fluid flow in an accretionary prism.

Results

On Expedition 311, we drilled a transect of four sites (U1325, U1326, U1327, and U1329) across the northern

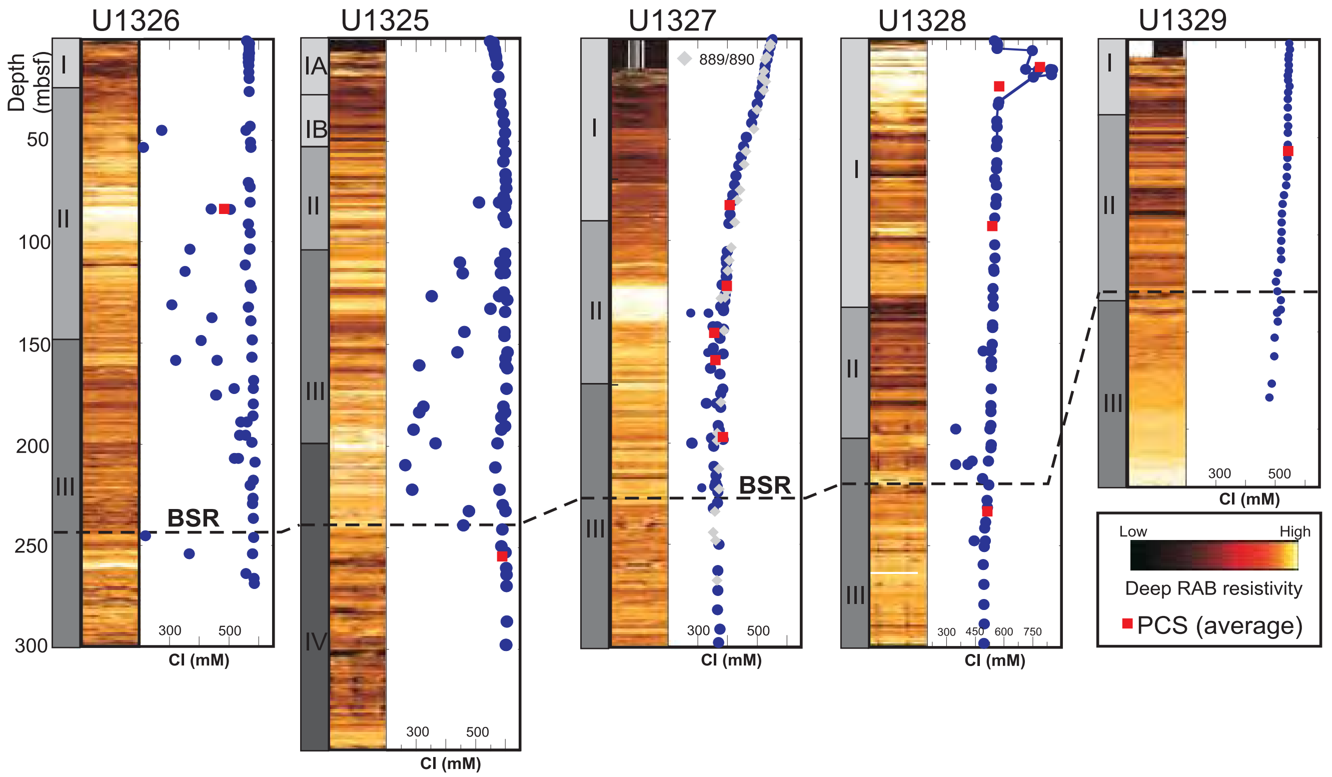

Figure 2. Summary of IODP Expedition 311 pore-water chlorinity profiles, including average chlorinity from PCS core. ODP Site 889 and 890 data are shown for comparison. Also shown are lithostratigraphic units, LWD RAB resistivity images, and location of BSR.

Cascadia margin and a fifth site (U1328) at a nearby cold vent with active fluid and gas flow. The four transect sites represent different stages in the evolution of gas hydrate across the margin from the earliest occurrence on the westernmost, first-accreted ridge (Site U1326) to its final stage at the eastward limit of gas-hydrate occurrence on the margin in shallower water (Site U1329). Logging-while-drilling and measurement-while-drilling (LWD/MWD) conducted prior to coring provided a set of measurements that guided subsequent coring and special tool deployments at all five sites. We also completed additional wireline logging at each site and two vertical seismic profiles (VSP) at Sites U1327 and U1328. A total of 1217.76 m of sediment core was recovered using the advanced piston corer (APC) and extended core barrel (XCB) systems. Standard coring was interspersed with pressure-core-sampler (PCS) runs for onboard degassing experiments and special Hydrate Autoclave Coring Equipment (HYACE) tools In New Tests on Hydrates (HYACINTH) pressure-coring deployments, four of which were stored under *in situ* pressure for subsequent shore-based studies.

Infrared imaging was used to identify quickly any gas hydrate that may have been present in the recovered core and that may have been available for direct sub-sampling and preservation with liquid nitrogen. Special care also was taken to sample cold infrared anomalies for pore-water chlorinity to confirm the presence of gas hydrate as well as sampling for shore-based microbiological analyses.

At each site, we tried to accomplish a three-hole conventional coring, specialized coring, and logging approach to maximize the scientific objectives. The first hole (Hole A) was always dedicated to LWD/MWD operations. All LWD/MWD holes were drilled during the first week of the expedition and were followed by coring and conventional wireline operations. In most cases, the second hole (Hole B) was for continuous coring, temperature measurements, and PCS coring to establish complete downhole profiles of gas-hydrate proxies such as pore-water chlorinity, infrared images, etc. The third hole (Hole C) was dedicated to special tool deployments, especially the two HYACINTH pressure-coring systems, the Fugro Pressure Corer (FPC) and HYACE Rotary Corer (HRC), and additional PCS deployments. In all coring holes, we tried to recover a detailed temperature profile by regularly deploying the Advanced Piston Corer Temperature tool (APCT), the third generation Advanced Piston Corer temperature tool (APC3) and the Davis-Villinger Temperature Pressure Probe (DVTPP); however, severe weather conditions during portions of the expedition resulted in degraded data quality for some deployments and in less-than-optimal constraints on the temperature gradient at all sites.

All results from the drilling transect and the cold-vent site are presented in Figures 2–4 as a collage of lithostratigraphic units and resistivity-at-the-bit (RAB) images from the LWD/MWD deployment compared with pore-fluid chlorinity (Fig. 2), sediment gas geochemistry (Fig. 3), and gas-hydrate concentration estimates using the RAB data (Fig. 4). The approximate depths of the BSR as predicted from seismic site-survey data are also shown.

Site U1326

Site U1326 is the westernmost site of the transect and is located on the first uplifted ridge of the accretionary wedge. Many faults intersect the sediment column from the seafloor to below the BSR. Newly acquired multibeam bathymetry data showed a prominent collapse feature near the original primary location, which forced a switch to the alternate site. The faults identified on the seismic data showed linear features on the bathymetry map crossing the ridge around the collapse feature and have seafloor displacements of up to 20 m.

The 271.4-m-thick Quaternary sedimentary section cored at Site U1326 is divided into three lithostratigraphic units. Soupy and mousse-like textures indicative of gas-hydrate occurrence are observed in Units II and III to a maximum depth of 246 mbsf.

At Site U1326, only one PCS core (Core 311-U1326C-12P; 83.7 mbsf) was recovered under pressure and investigated by controlled shipboard degassing experiments. LWD/MWD-derived RAB images from Hole U1326A indicate the presence of high-resistivity gas-hydrate intervals between 72 and 240 mbsf (Figs. 2–4). Gas-hydrate-rich layers alternate with low-resistivity layers that likely contain little or no gas hydrate. Calculation of water saturations from electrical-resistivity logging data yield evidence for relatively shallow gas-hydrate occurrences at this site between ~50 and 100 mbsf, with inferred gas-hydrate concentrations as high as 80% of the pore space. P-wave velocities measured by wireline logging in Hole U1326D show highly variable values (between 1750 and >3000 $m \cdot s^{-1}$) in the same high-resistivity interval. The high P-wave velocity values are consistent with high gas-hydrate concentrations.

The chlorinity data from Site U1326 show an almost constant baseline trend of near seawater values with depth (Fig. 2). Chlorinity anomalies associated with gas hydrate actually may extend to 270 mbsf at this site, which is deeper than the estimated BSR depth of 230 mbsf. This apparent disparity between the predicted depth of the BSR and the observed occurrence of gas hydrate may be explained by the borehole temperature measurements that yield a methane-hydrate stability zone depth of 275 ±25 mbsf; however, most data from the temperature tool deployments are degraded, and we have extrapolated the temperature data from Site U1325 for this calculation.

Hydrocarbon headspace-gas measurements from Holes U1326C and U1326D show that methane is the dominant hydrocarbon gas within the cored interval (Fig. 3). The C_{2+} hydrocarbon void-gas concentrations are <125 ppmv (parts per million by volume) for all samples. Low C_1/C_2 ratios within the interval from ~35 to ~72 mbsf are associated with two recovered gas-hydrate samples. With greater depth, ethane concentrations return to the near-surface concentrations close to the predicted depth of the BSR. Isobutane concentrations are also elevated within the same interval, which may indicate the presence of Structure II gas hydrate. The occurrence of more complex hydrocarbon gases in combination with the pore-water chlorinity baseline shift with depth generally indicates the contribution of a deeper gas source.

Site U1325

Site U1325 is located near the southwestern end of the drilling transect and lies within a major slope basin that developed eastward of the deformation front behind a steep ridge of accreted sediments (Fig. 1). The site is underlain by a relatively weak BSR, which appears to be at 230 ± 5 mbsf using simple seismic travel-time depth conversion with an average P-wave velocity of 1636 $m \cdot s^{-1}$ as defined from the ODP Site 889 VSP survey (MacKay et al., 1994).

Four holes were occupied at Site U1325. Hole U1325A was dedicated to the pre-coring LWD/MWD deployment, and Holes U1325B, U1325C, and U1325D recovered a 304.3-m-thick sediment section that was divided into four lithostratigraphic units based on visual inspection of the recovered cores. Examination of diatoms from Holes U1325B and U1325C indicated that the sediments cored at Site U1325 are mostly Quaternary in age.

Pressure coring proved difficult at this site. Out of the seven attempts using the PCS, FPC and HRC, only the deepest PCS (256.5 mbsf) recovered sediment under pressure.

LWD/MWD-derived RAB images from Hole U1325A suggested that gas hydrate is concentrated in thin sand layers between 173 and 240 mbsf (Figs. 2–4). The LWD/MWD porosity and resistivity logs showed further that it is a very heterogeneous gas-hydrate-bearing section composed of alternating layers of gas-hydrate-saturated sands and clay-rich layers with little to no gas hydrate. This interpretation generally agrees with the marked freshening of the interstitial water observed in sampled sand layers.

The salinity and chlorinity profiles indicate an advective transport system with the occurrence of higher-than-seawater salinity and chlorinity values of ~36 and ~600 mM, respectively (Fig. 2). The elevated solute concentration might be caused by low-temperature diagenetic hydration reactions, probably the alteration of volcanic ash to clay minerals or zeolites in the deeper parts of the basin. In the zone extending from ~70 to 240 mbsf, salinity and chlorinity data show discrete excursions to fresher values, indicating that gas hydrate was present in the cores and had dissociated prior to processing the samples.

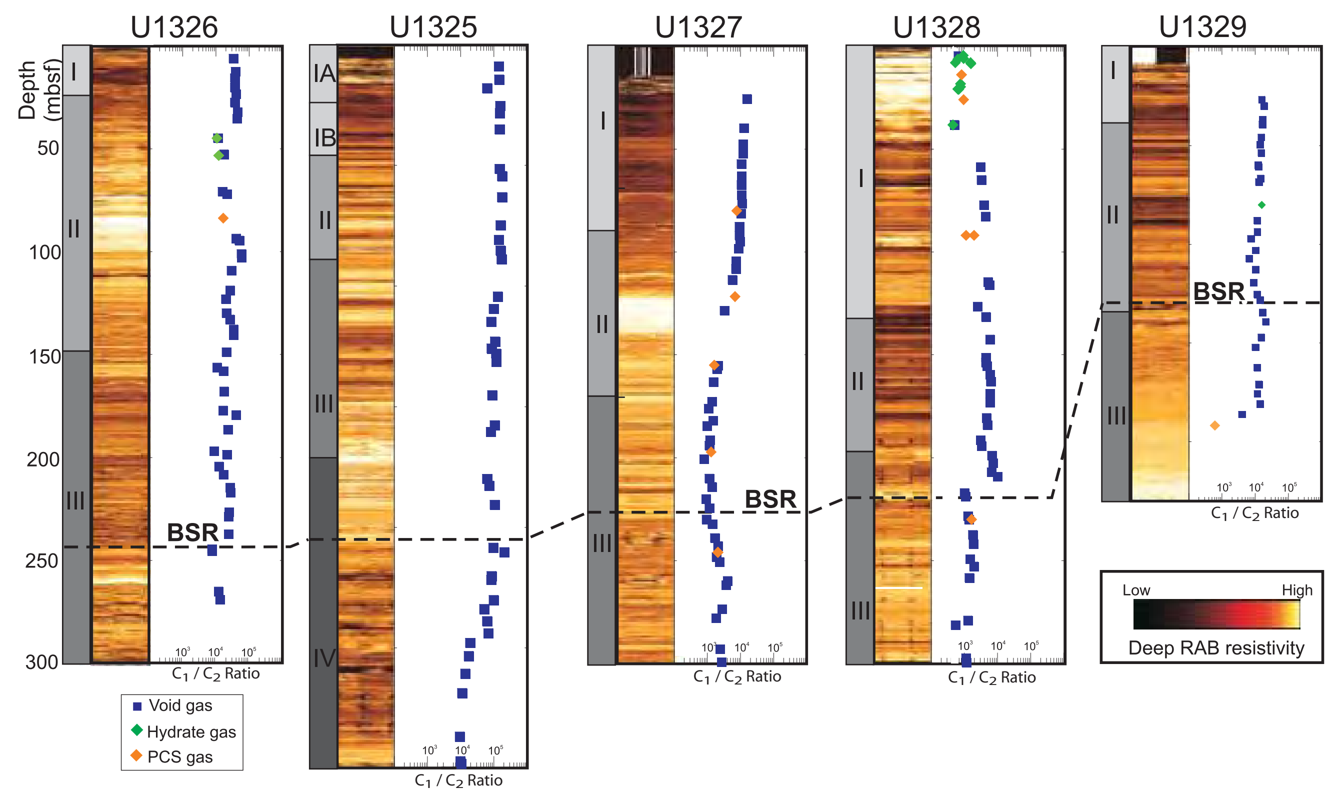

Figure 3. Summary of Expedition 311 C_1/C_2 gas profiles, including data from void, gas hydrate, and PCS gas. Also shown are lithostratigraphic units and LWD RAB resistivity images and location of BSR.

Organic geochemical studies of headspace samples, void gas, and gas samples recovered during the PCS degassing experiment indicate that the recovered gas was almost entirely methane with a small percentage of carbon dioxide (~0.1–0.5%). Trace quantities of C_{2+} hydrocarbons (<5 ppmv) are present above the predicted BSR depth (Fig. 3). With greater depth, the concentrations of ethane, propane, and isobutane increase but do not exceed 15 ppmv. Decreasing C_1/C_2 values below the BSR indicate a slight thermogenic or diagenetic contribution of ethane.

Site U1327

Site U1327 is located near ODP Sites 889 and 890 (Westbrook et al., 1994), approximately at the mid-slope of the accretionary prism over a clearly defined BSR estimated at 223 mbsf. Site U1327 is located near two prominent topographic highs rising >200 m above the surrounding seafloor and is characterized by a ~90-m-thick cover of slope-basin sediments underlain by a thick section of accreted sediments (Fig. 1). The 300-m-thick sediment section recovered at Site U1327 is divided into three lithostratigraphic units, with the boundary between Units I and II coinciding with the seismostratigraphic boundary between slope and accreted sediments. Soupy and mousse-like sediment textures related to the presence of observed gas hydrate are detected only in Unit II to a maximum depth of 161.85 mbsf.

From 128 mbsf to the depth of the BSR, the chlorinity and salinity profiles exhibit distinct anomalies that indicate freshening as a result of the dissociation of gas hydrate during the core recovery process (Fig. 2). Chloride values as low as 70 mM (salinity = 3.7) correlate to individual turbidite sand layers. Such a low pore-water chlorinity is equivalent to a pore-space gas-hydrate concentration of ~80%. No chlorinity anomalies occur below ~225 mbsf, which is close to the predicted depth of the BSR. The strongly decreasing chlorinity profile from the surface to below the BSR suggests mixing between *in situ* seawater and deeply sourced, modified, relatively fresh pore water. Pore-water chlorinity and salinity remain almost constant beneath the BSR.

Methane is the predominant hydrocarbon gas found in the cores from Site U1327. Ethane concentrations are generally low but increase in the void and headspace gases collected from the stratigraphic section overlying the projected depth of the BSR. This increase in ethane concentrations is reflected in the C_1/C_2 void gas ratios, which decrease with depth toward the BSR (Fig. 3).

Pre-coring LWD/MWD in Hole U1327A showed a thick section of consistently high electrical resistivities and low density values at a depth of 120–138 mbsf. This section was the target of several pressure cores in the adjacent holes, but we failed to recover core under pressure. Calculated values of pore-water saturation suggest gas-hydrate concentrations as high as 50% of the pore volume in this interval; however, the same interval was penetrated in the adjacent Holes

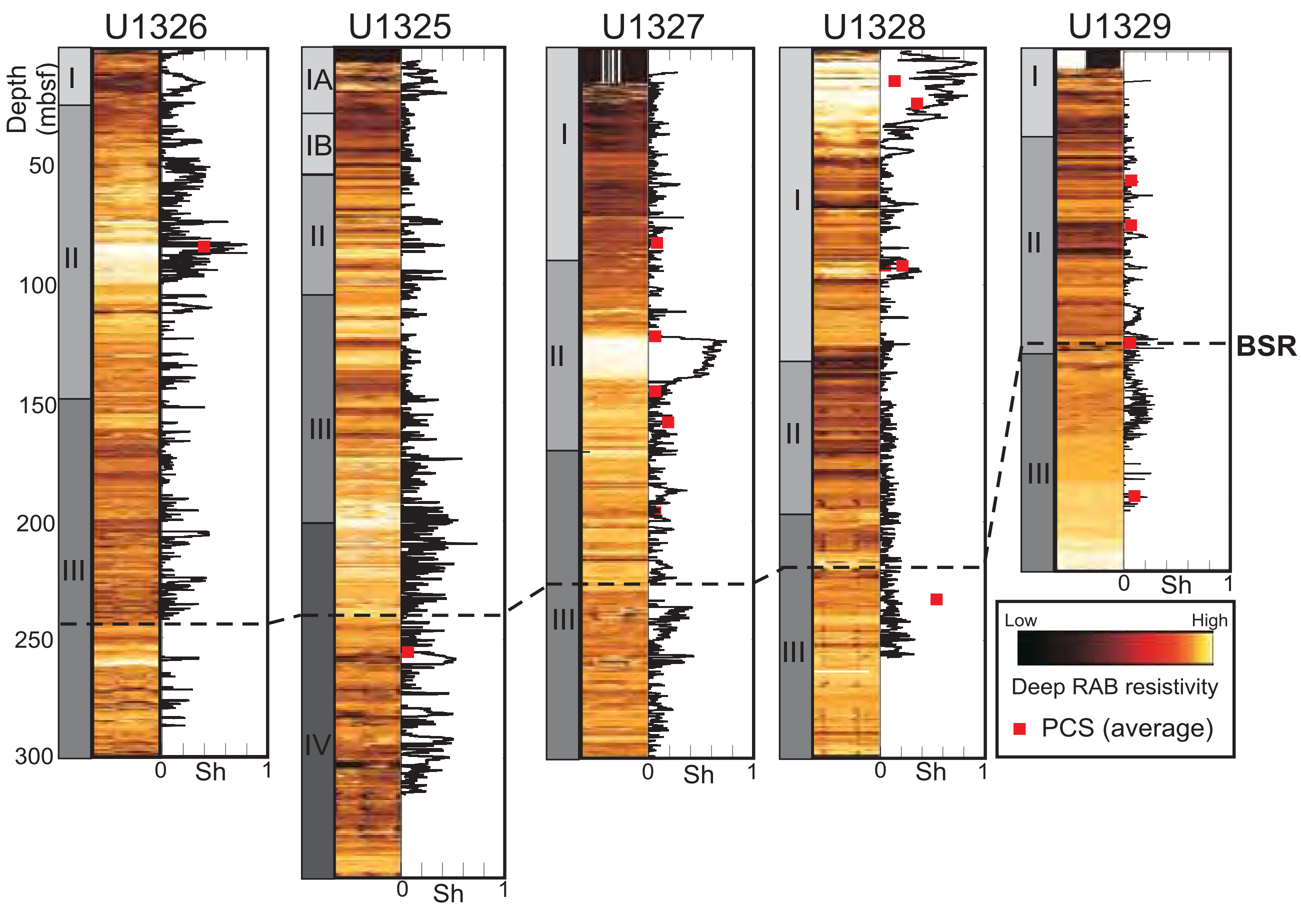

Figure 4. Summary of Expedition 311 gas hydrate concentration (Sh) derived from LWD data using Archie's Relation. Also shown are lithostratigraphic units and LWD RAB resistivity images and location of BSR.

U1327C and U1327D at much greater depths and with lower estimated gas hydrate concentrations inferred from the wireline electrical log in Hole U1327D. No evidence of this interval was found in the wireline logs in Hole U1327E. This demonstrates large intrasite variability in gas hydrate content that is probably controlled by lithostratigraphic changes or structural complexities. This observation has dramatic implications on the calibration of geophysical surveying techniques such as seismic methods or controlled-source electromagnetic surveys that are commonly used to detect and quantify gas hydrate.

Site U1329

Site U1329 lies at the eastern end of the drilling transect and is believed to be at the eastern limit of gas hydrate occurrence on the northern Cascadia margin. A faint BSR was identified in the site-survey data at ~126 mbsf. Site U1329 is located near the foot of a relatively steep slope, and sedimentation at this site is dominated by slope processes. The stratigraphy at Site U1329 is divided into three lithostratigraphic units with the boundary between Units II and III marked by the occurrence of an unconformity. Biostratigraphic analyses show that sediments of Unit III are of late Miocene age (> 6.7 Ma), whereas sediments in Unit II range from 0.3 to 2.0 Ma. The unconformity thus represents ~4 m.y. of missing sediment which was likely eroded.

The recovered sedimentary section did not show any signs of prominent infrared anomalies or soupy or mousse-like textures indicative of the presence of gas hydrate. Similarly there are no obvious anomalies in the pore-water chlorinity profile (Fig. 2).

The predominant hydrocarbon gas found in the cores from Site U1329 is methane. The C_1/C_2 ratios are generally high, suggesting a microbial origin for the observed methane (Fig. 3). Samples collected from deeper than 180 mbsf at this site, however, exhibited significant increases in C_2–C_5 concentrations, which suggests an influence from a thermogenic hydrocarbon source.

Site U1328

Site U1328 is located within a seafloor cold-vent field consisting of at least four vents associated with near-surface faults. The cold vents are characterized by seismic blank zones that are between eighty and several hundred meters wide and show a clear east-west trend as identified from 3-D seismic imaging (Riedel et al., 2002). We targeted the most prominent vent in the field, referred to as Bullseye vent, which has been the subject of intensive geophysical and geochemical studies since 1999 (e.g., Riedel et al., 2006; Wood et al., 2002). Site U1328 differs from the four other sites visited during this expedition in that it represents an area of active, focused fluid flow. Several mechanisms have been proposed to explain the seismic blanking and nature of fluid venting in the Bullseye vent area (Riedel et al., 2002, 2006; Zuehlsdorff and Spiess, 2004; Wood et al., 2002). The objectives of coring and logging at this location were to test the different models for the cold-vent structure and associated causes of seismic blanking, the rate of methane advection, and the potential loss of methane into the water column.

Five holes were drilled at Site U1328. Hole U1328A was dedicated to LWD/MWD measurements to a total depth of 300 mbsf. At Site U1328, a 300-m-thick sequence of Quaternary (0 to <1.6 Ma) slope and slope basin sediment was recovered in Holes U1328B, U1328C, and U1328D and was divided into three lithostratigraphic units. Hole U1328E was used to conduct a VSP experiment with the deepest clamping position at 286 mbsf.

At Site U1328, massive gas hydrate was sampled near the seafloor, and evidence of gas hydrate was found in the recovered cores in the form of soupy and mousse-like textures and cold infrared anomalies.

The most striking feature in the LWD/MWD logs from site U1328 is the occurrence of layers with high resistivities (>25 Ωm) alternating with zones of lower resistivity (1–2 Ωm) in the upper 46 mbsf. The high resistivities likely indicate the presence of gas hydrate. Below this uppermost high-resistivity zone, the LWD/MWD logs do not show much evidence for the presence of gas hydrate, except for a few intervals where steeply dipping fractures with high resistivity values, probably the result of gas hydrate, were penetrated. These fractures might act as gas migration conduits that feed the gas-hydrate accumulation observed near the seafloor.

The combined analysis of wireline logging, acoustic velocities, and waveform amplitudes identify the occurrence of free gas in the interval between 210 and 220 mbsf, near the predicted depth of the BSR at ~219 mbsf in Hole U1328C, where the P-wave velocity drops slightly and the S-wave velocity increases. Additional evidence for the occurrence of free gas below the BSR is noted in the analysis of the LWD/MWD acoustic coherence data, borehole fluid-pressure response during drilling, and the wireline P-wave, resistivity, density, and neutron logs. The PCS degassing experiments of a single core in Hole U1328E also indicate the presence of a free gas phase below the BSR at this site; however, the VSP experiment conducted in Hole U1328E yielded uniform velocities near 1645 $m \cdot s^{-1}$ for the entire depth range between 105 and 286 mbsf and thus did not show any sign of gas hydrate or free gas.

The composite chlorinity profile for this site shows four distinct zones (Fig. 2). In the upper ~40 m of the hole, a striking increase in chlorinity is seen with maximum values exceeding 850 mM. This is interpreted as a result of salt exclusion during *in situ* gas-hydrate formation that has not been removed by advective or diffusive processes. The second zone from ~40 to ~150 mbsf is characterized by linearly decreasing chlorinity values ranging from 538 to 570 mM. A third zone, extending ~150–250 mbsf across the BSR, showes discrete excursions to fresher chlorinity values as low as 348 mM, suggesting that gas hydrate was present in the cores and had dissociated prior to processing the samples. In the deepest zone, below 250 mbsf, the chlorinity remains nearly constant at 493 ±3 mM, suggesting communication with a fluid at greater depth that is notably different in composition from the deep-seated fluid sampled at Sites U1327 and ODP Sites 889 and 890.

Geochemical analyses of headspace and void-gas samples show that methane is the most prominent hydrocarbon gas at Site U1328 (Fig. 3). Ethane was also present in almost all of the headspace samples, and the concentrations of ethane, propane, and isobutane increase at and below the predicted depth of the BSR. The occurrence of propane and elevated isobutane to n-butane ($i\text{-}C_4/n\text{-}C_4$) ratio suggests that the gas hydrate near the BSR contains Structure II gas hydrate.

Summary

IODP Expedition 311 established the first margin-wide transect of drilling sites through an accretionary prism expressly to study gas hydrate. The sites represent various stages in the gas-hydrate formation history capturing typical accretionary wedge environments such as accreted ridges and slope basins filled with either undisturbed or slightly deformed slope sediments and accreted sediments that lack seismic coherency as a result of tectonic stresses.

Indirect evidence of the presence of gas hydrate includes increased electrical resistivities and P-wave velocities on downhole logs, low chlorinity and low salinity pore-water anomalies, numerous infrared cold spots, and decreases in void gas C_1/C_2 ratios, as well as moussey and soupy sedimentary textures in recovered cores. Gas hydrate was also observed directly in recovered cores, and more than thirty gas hydrate samples were preserved in liquid nitrogen for shore-based studies.

The combined observations along this transect of sites show that gas hydrate occurs within coarser-grained turbidite sands and silts. The occurrence of gas hydrate appears to be controlled by several factors, including (1) local methane solubility linked with pore-water salinity, (2) fluid and gas advection rates, and (3) the availability of suitable host material such as coarse-grained sediments. The concentration of gas hydrate in the sediment changes significantly as these factors vary along the margin.

In previously published models of gas hydrate formation in an accretionary margin, the highest concentrations of gas hydrate were expected to occur near the base of the gas-hydrate stability zone above the BSR, with concentrations gradually decreasing upward as a result of pervasive fluid advection from overall tectonically driven fluid expulsion. The results of Expedition 311, however, show that this model is too simple and that there are additional controlling factors. Although the data should provide evidence for widespread gas-hydrate-related BSRs, by far the largest concentrations of gas hydrate are observed well above the base of the gas-hydrate stability zone, at a point where the amount of methane in the pore fluid exceeded the local methane solubility threshold. This condition was most evident at Sites U1326 and U1327, where gas hydrate was observed in sections several tens of meters thick at shallow depths of ~100 m and at concentrations exceeding 80% of the pore volume. Another site of very high gas-hydrate concentrations was the cold vent Site U1328, where beds containing massive forms of gas hydrate occurred within the top ~40 m at concentrations exceeding 80% of the pore space, as a result of fluid and gas migrating upward along the underlying fault systems.

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The Lake Petén Itzá Scientific Drilling Project

by David Hodell, Flavio Anselmetti, Mark Brenner, Daniel Ariztegui,
and the PISDP Scientific Party

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Introduction

Polar ice cores provide us with high-resolution records of past climate change at high latitudes on both glacial-to-interglacial and millennial timescales. Paleoclimatologists and climate modelers have focused increasingly on the tropics, however, as a potentially important driver of global climate change because of the region's role in controlling the Earth's energy budget and in regulating the water vapor content of the atmosphere. Tropical climate change is often expressed most strongly as variations in precipitation, and closed-basin lakes are sensitive recorders of the balance between precipitation and evaporation. Recent advances in floating platforms and drilling technology now offer the paleolimnological community the opportunity to obtain long sediment records from lowland tropical lakes, as illustrated by the recent successful drilling of Lakes Bosumtwi and Malawi in Africa (Koeberl et al., 2005; Scholz et al., 2006).

Tropical lakes suitable for paleoclimatic research were sought in Central America to complement the African lake drilling. Most lakes in the Neotropics are shallow, however, and these basins fell dry during the Late Glacial period because the climate in the region was more arid than today. The search for an appropriate lake to study succeeded in 1999 when a bathymetric survey of Lake Petén Itzá, northern Guatemala, revealed a maximum depth of 165 m, making it the deepest lake in the lowlands of Central America (Fig. 1). Although the lake was greatly reduced in volume during the Late Glacial period, the deep basin remained submerged and thus contains a continuous history of lacustrine sediment deposition. A subsequent seismic survey of Lake Petén Itzá in 2002 showed a thick sediment package overlying basement, with several subbasins containing up to 100 m of sediment (Anselmetti et al., 2006).

Site Location

Lake Petén Itzá is located at ~16°55' N, 89°50' W in the Department of Petén, northern Guatemala, and has a surface area of 100 km^2 (Fig. 1). Maximum water depth is 165 m, and the surface elevation is only 110 m above sea level. This means the deepest basin is a cryptodepression that extends to ~55 m below present sea level. The lake is located in a climatically sensitive region where rainfall is highly seasonal

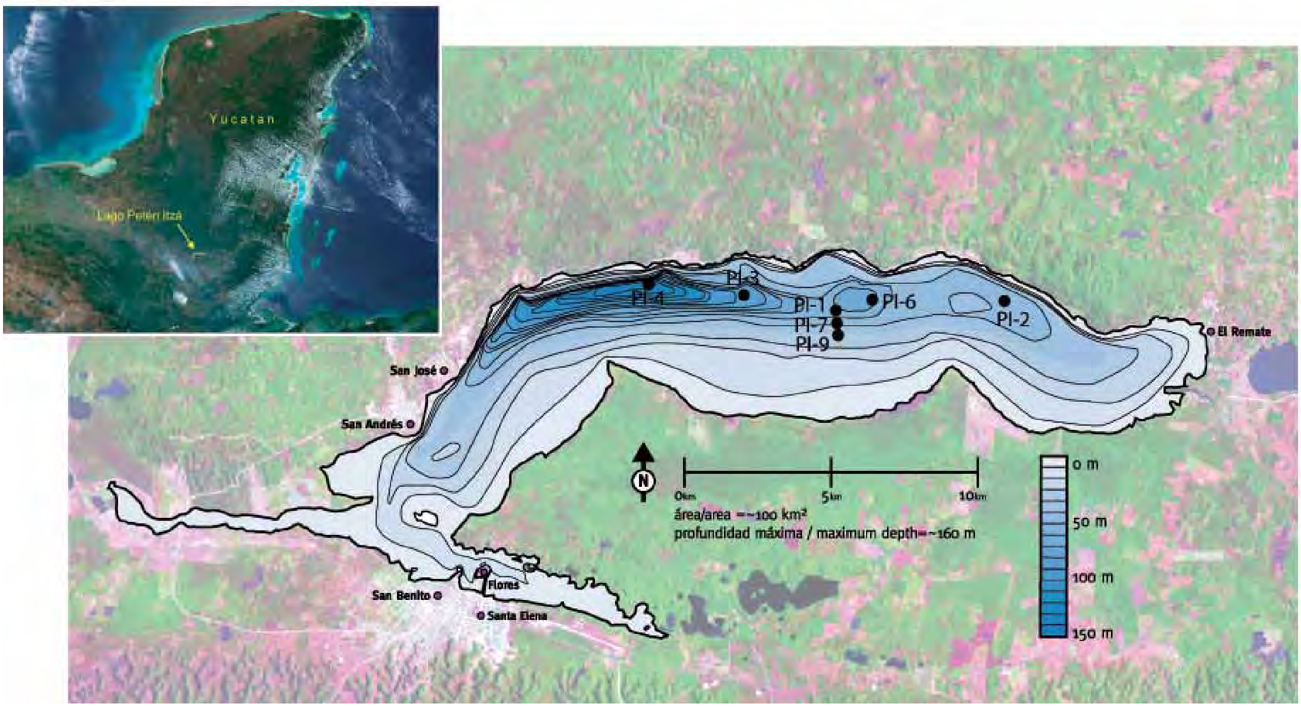

Figure 1. Inset satellite image shows location of Lake Petén Itzá on Yucatan Peninsula. Bathymetric map shows location of drilling sites .

Table 1: Location of drilling sites, water depth, penetration, and core recovery at Lake Petén Itzá

Site	Latitude	Longitude	Water Depth(m)	Penetration Depth (meters below lake floor)					Average Recovery
				Hole A	Hole B	Hole C	Hole D	Hole E	
PI-1	16° 59.9706' N	89° 47.7396' W	65	94.5	90.3	82.5			89.3
PI-2	16° 59.9712' N	89° 44.685' W	54	66.5	41.2	82.4	42.0	68.5	86.3
PI-3	17° 0.2016' N	89° 49.24' W	100	96.9	95.3	90.0			92.9
PI-4	17° 0.3342' N	89° 50.772' W	150	67.4	46.1	25.4			86.7
PI-6	17° 0.0162' N	89° 47.0868' W	71	75.9	66.4	66.8			94.9
PI-7	16° 59.7234' N	89° 47.6844' W	46	133.2	122.8	63.8			92.1
PI-9	16° 59.436' N	89° 47.646' W	30	16.4					91.8

and related to the seasonal migration of the Intertropical Convergence Zone (ITCZ). The lake water today has a high pH (~8.0) and a low total ionic concentration (12.22 meq·l^{-1}) dominated by calcium, magnesium, sulfate, and bicarbonate, and it is saturated for calcium carbonate. During the Late Glacial period, the lake volume was reduced by 87%, and the water was saturated for gypsum (Hillesheim et al., 2005).

The Petén Lake District has been a region of paleoenvironmental study for over thirty years, with most investigations focused on Holocene paleoecologic reconstruction, especially the impact of the Maya civilization on the lowland tropical environment. Previous studies showed that the region underwent profound climatic and environmental change from the arid Late Glacial period to the moist early Holocene, but the climate history on millennial or shorter time scales is not known for the last glacial period, and no paleoclimatic data exist beyond ~36 ka.

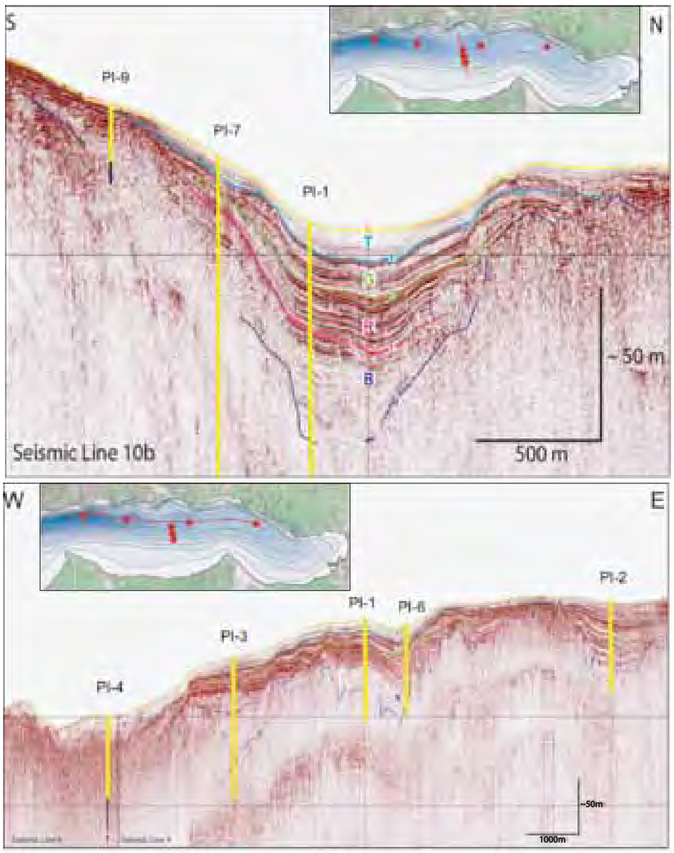

Figure 2. Top: Airgun seismic profile line 10b oriented N-S with drilling penetration depths of Sites PI-9, PI-7, and PI-1. Bottom: Airgun seismic profiles 8 and 9 oriented E-W with drilling penetration depths of Sites PI-2, PI-6, PI-1, PI-3, and PI-4 (Site PI-1 projected). Inset lake maps shows position of seismic lines.

Objectives and Operations

The primary purpose of the Lake Petén Itzá Scientific Drilling Project (PISDP) was to recover complete lacustrine sediment sequences to study the following:

- the paleoclimatic history of the northern lowland Neotropics on decadal to millennial timescales, emphasizing marine-terrestrial linkages (e.g., correlation to Cariaco Basin, Greenland ice cores, etc.)
- the paleoecology and biogeography of the tropical lowland forest, such as the response of vegetation to disturbance by fire, climate change, and humans
- the subsurface biogeochemistry, including integrated studies of microbiology, porewater geochemistry, and mineral authigenesis and diagenesis

Drilling operations were conducted in February–March 2006 by Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC), Inc., using the Global Lake Drilling platform, GLAD 800 (Fig. 2). All primary sites (PI-1, PI-2, PI-3, PI-4, PI-7, and PI-9) and one alternate site (PI-6) were drilled with an average core recovery of 93.4% (Table 1). A total of 1327 m of sediment was recovered, and the deepest site (PI-7) reached 133 m below the lake floor. Multiple holes were drilled at most sites, and cores were logged in the field for density, p-wave velocity, and magnetic susceptibility using a GEOTEK core logger provided by the International Continental Scientific Drilling Program (ICDP). Complete stratigraphic recovery was verified in nearly real time using Splicer, a software program developed by the Ocean Drilling Program that permits alignment of features among holes using core logging data. Downhole logging was conducted by the ICDP Operational Support Group (OSG) at five sites using their slimhole logging tools. Samples from at least one hole from most of the primary sites were squeezed for pore-water geochemical analysis, and ephemeral properties such as alkalinity and pH were measured on site. Smear-slides were prepared from core-catcher samples to describe lithologic changes at each site. Cores were stored onsite in a refrigerated container that was shipped to the National Lacustrine Core Repository (LacCore) at the University of Minnesota (U.S.A.), where initial core descriptions are under way. All data collected on the drilling platform and in the field laboratories were entered into the ICDP Drilling Information System (DIS), uploaded with daily reports and photos to the servers at the GeoForschungsZentrum, Potsdam, Germany, and made available online (http://peten-itza.icdp-online.org).

Preliminary Results

Two shallow sites (PI-9 and PI-7) were drilled in 30 m and 46 m water depth to a maximum depth below the lake floor of 16.4 m and 133.2 m, respectively (Table 1). The great thickness of sediment at PI-7 was surprising, as basement was thought to lie much shallower, at ~47 m (Fig. 2). The shallow sites were not expected to yield long, continuous lacustrine records because relatively short (<6 m) piston cores at these water depths contain paleosols, indicating subaerial exposure during the Late Glacial period (Hillesheim et al., 2005). Shallow-water facies consist primarily of carbonate-rich sediment with abundant shell material, gypsum sand, and indurated gypsum crusts. Deep-water facies consist of diatom-rich, gray to brown clay that was deposited during lake highstands.

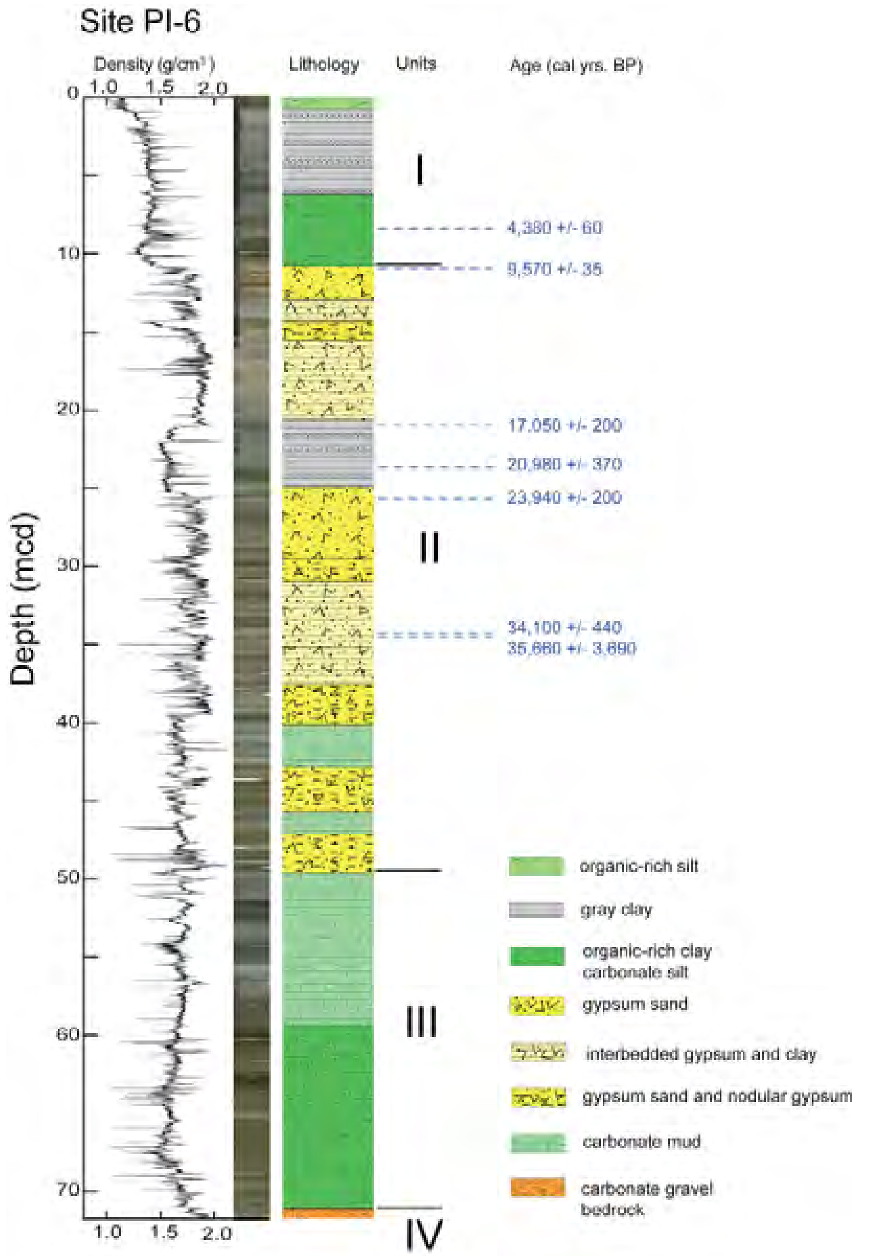

Figure 3. Density, core images, and lithostratigraphy for composite section of Site PI-6. Positions of calibrated radiocarbon dates on terrestrial organic matter are indicated.

Continuous lacustrine deposition was expected for the intermediate (PI-1, PI-2, and PI-6) and deep-water sites (PI-3 and PI-4), with lowstands represented by shallow-water facies (e.g., gypsum sand), especially at the sites of intermediate water depth. Intermediate Site PI-2 is located in the eastern basin that was separated from the central basin during times of greatly reduced lake level (Fig. 1), thereby providing an opportunity to study a semi-independent basin during lowstands. At the deepest sites (PI-3 and PI-4), we were concerned about potential downslope transport, and, indeed, clear evidence of slumping (tilted beds) and sediment disturbance was observed in parts of the section at both sites.

The lithostratigraphy is similar for the intermediate- and deep-water sites, and four lithostratigraphic units are defined on the basis of preliminary core-catcher descriptions and the split cores of Site PI-6. The boundaries between Units I, II, III and IV also correspond to changes in the character of the bulk-density curve and to changes in the seismic profiles (Figs. 3 and 4). Uppermost Unit I, coinciding with seismic sequence T (Fig. 2), consists primarily of gray clay with abundant charcoal, and this unit has been recovered previously from the basin in numerous Kullenberg piston cores (Hillesheim et al., 2005). Unit I spans the entire Holocene, but the bulk of the clay was deposited in a relatively short period between ~3000 and 1000 yrs BP as a consequence of soil erosion brought about by deforestation of the watershed for Maya agriculture. Unit II coincides approximately with seismic sequences G and R (Fig. 2) and consists of interbedded dense gypsum sand, clay, and carbonate mud that were deposited during the latest Pleistocene. The boundary

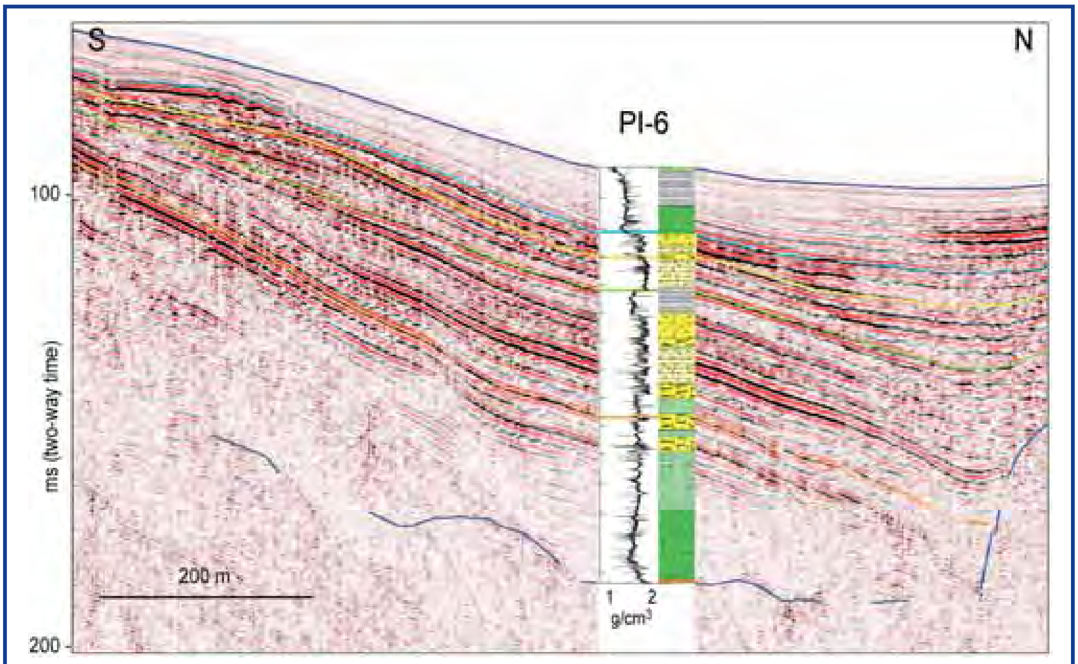

Figure 4. Composite record of MSCL-bulk density and lithology superimposed on seismic data for Site PI-6. Color code of lithologic section is indicated in Figure 3.

between Units II and I coincides with the Pleistocene/ Holocene boundary and reflects a transition from an arid climate during the Late Glacial period to a moist climate during the early Holocene (Hillesheim et al., 2005). The boundary corresponds to a sharp change in sediment density (Figs. 5 and 6).

High-frequency variations in bulk density occur throughout lithologic Unit II and can be correlated among sites in the deep basin (Fig. 5). These density changes reflect alternating beds of gypsum and clay-rich sediment, which represent lake-level lowstands (gypsum) and highstands (clay). Initial radiocarbon dates suggest an average sedimentation rate for the upper 35 mcd of about 1 m per thousand years. Unit III occurs below the gypsiferous deposits and correlates roughly to seismic sequence B (Fig. 2). It consists of a thick sequence of organic-rich carbonate clay and silt that is rich in diatoms and carbonate microfossils. The age of Unit III is not yet known, but radiocarbon and U/Th measurements are under way to date these deposits. At the bottom of the holes, Unit IV consists of gravels and angular pieces of indurated carbonate rock that likely represent bedrock.

One unexpected finding was the common occurrence of elemental sulfur nodules at several sites (Fig.6). These nodules form post-depositionally as they cut across bedding and tend to occur at the transitions from gypsum to clay facies. We speculate that abundant sulfate, both in the water column and at depth in the sediment, promotes sulfate reduction and production of H_2S. In the absence of abundant Fe, the H_2S may then be oxidized to elemental S. An integrated program of subsurface microbiology and pore-water geochemistry is planned to study this process.

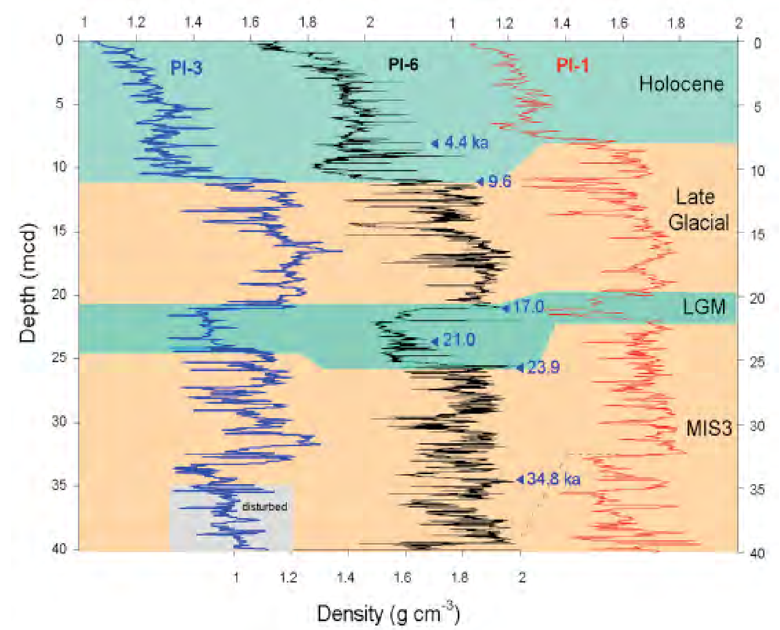

Figure 5. Correlation of composite density records for upper 40 m of Sites PI-3 (water depth =100 m), PI-6 (water depth = 71 m), and PI-1 (water depth =65 m) from Lake Petén Itzá's central basin. Calibrated radiocarbon dates on terrestrial organic matter are indicated from Site PI-6. LGM = Last Glacial Maximum; MIS3 = Marine Isotope Stage 3

Downhole logging with slimline tools was conducted at five sites (PI-1, PI-2, PI3, PI-4, and PI-7) both through the drill pipe and in the open borehole where conditions permitted. Natural and spectral gamma radiation tools were run through the cased hole at all sites. Similar natural gamma radiation measurements are being made on whole cores, and these measurements will permit core-log integration and construction of another depth scale (i.e., equivalent logging depth) that will correct for stretching or compression of the cores. Comparison of core and borehole logging data with seismic profiles will enable correlation of seismic reflections to lithologic changes and development of a seismic sequence stratigraphy for the entire lake basin.

Figure 6. Sulfur nodule from ~99 to 101 cm in Core 6A-4H-2 near Pleistocene-Holocene boundary. Nodule formed near interface between underlying gypsum sand (Unit II) below and overlying clay (Unit I).

Summary

The Petén Itzá Scientific Drilling Project achieved all of its field objectives and recovered 1327 m of high-quality core at seven sites. Preliminary results with respect to sediment lithology, density, magnetic susceptibility, and downhole natural gamma logs display a high degree of climate-related variability that can, in some cases, be correlated among sites. The overall post-drilling objective will be to place this variability in a firm chronologic framework and decipher the history of the northern Neotropic hydrologic cycle, its relation to changes in the position of the Atlantic ITCZ, and linkages to climate variability in the region (e.g., Cariaco Basin) and elsewhere (e.g., high-latitude North Atlantic).

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Building a Natural Earthquake Laboratory at Focal Depth (DAFSAM-NELSAM Project, South Africa)

by Ze'ev Reches and the DAFSAM and NELSAM teams

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Introduction

The study of faulting and earthquake processes requires direct and near-field observations at the focal depth. Deep mines provide a unique opportunity to make such observations. The linked DAFSAM (Drilling Active Faults Laboratory in South African Mines)-NELSAM (Natural Earthquake Laboratory in South African Mines) projects focus on building an earthquake laboratory in deep gold mines in South Africa.

Gold is produced from the massive Precambrian sequence of the Witwatersrand basin by sub-horizontal mining at depths of 1.5–3.5 km. During the lifetime of a mine, the gradual closure of the open space of the mine shafts and tunnels releases gravitational energy that induces intense seismic activity. Mine seismicity has been investigated extensively (e.g., McGarr et al, 1979; Mendecki, 1997), and mining-related earthquakes were found to resemble natural tectonic earthquakes in some ways but not in others (e.g., McGarr, 1999; Richardson and Jordan, 2002). Two types of mining-induced events have been recognized—those that are induced directly by mining operations (e.g., rock bursts) and those related to movements along major faults and dykes. The earthquake laboratory focuses on the second type, showing greatest potential for comparison with naturally occurring earthquakes.

Hundreds to thousands of small to moderate earthquakes per day are recorded in a typical deep mine; the strongest may reach an intensity of magnitude 5. Given that many of these earthquakes are controlled directly by the mining activity, their location, timing, and magnitude can be forecast, and instruments can be installed at sites where earthquakes of interest are predicted to occur. The mine infrastructure provides access to the earthquakes' source region and allows three-dimensional mapping of the fault zone. It also allows installation of a three-dimensional array of instruments 1–100 m from an anticipated hypocenter to monitor fault activity before, during, and after an earthquake. Most expected earthquakes exhibit a moment-magnitude range (-2 to 4) that bridges the scale gap between laboratory experiments and tectonic earthquakes in the crust. The mine infrastructure provides an opportunity to investigate the effects of fracturing during earthquakes on fault fluid, gas chemistry, and microbiological communities. These promising conditions have led to the building of an earthquake laboratory in the TauTona gold mine in January 2005 as part of the DAFSAM-NELSAM project.

The Laboratory Site at TauTona Mine

The TauTona ("great lion" in Sotho) gold mine, the deepest mine on Earth, is located about 80 km west of Johannesburg within the Western Deep Levels of the Witwatersrand basin (Fig.1). The gold deposit is mined at 2–3.5 km depths, with a planned deepening to almost 4 km over the next decade. The deepening is facilitated by constructing two declined shafts that cut across the Pretorius fault (Fig. 2), the largest fault in the western deep area of the mine. We chose the section of the Pretorius fault that intersects the two declined shafts as the most promising site for the DAFSAM-NELSAM earthquake laboratory (Fig. 2). The fault cuts across the slightly metamorphosed Precambrian sedimentary rocks of the Witwatersrand basin, mainly quartzite, conglomerates, and mudrocks, as well as basaltic bodies. The region has been

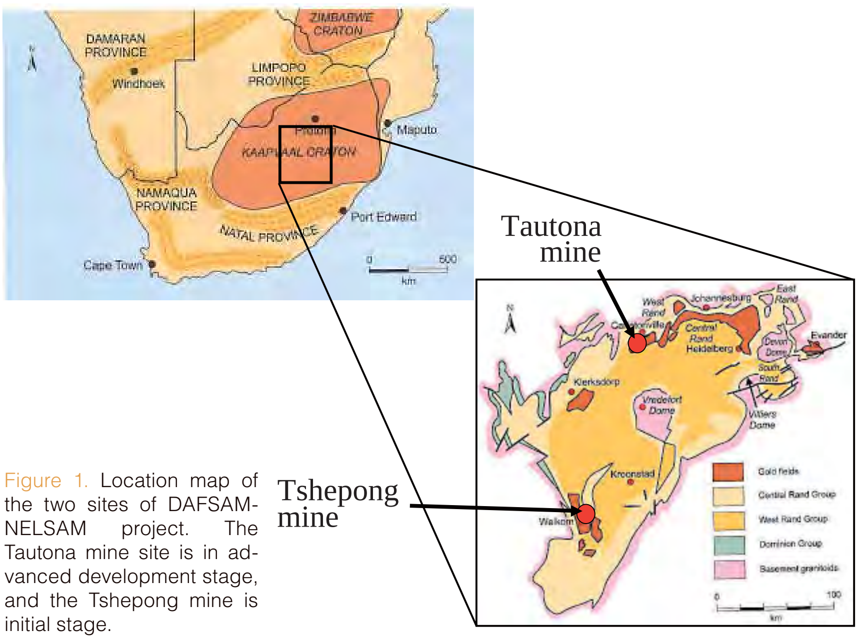

Figure 1. Location map of the two sites of DAFSAM-NELSAM project. The Tautona mine site is in advanced development stage, and the Tshepong mine is initial stage.

tectonically inactive for the last 2.5 Ga. The Pretorius fault is at least 10 km long, trending east-northeast, with a vertical throw of 30–60 m and an estimated right-lateral displacement up to 200 m. It has a 25–30-m-wide fault zone with tens of anastomosing segments, dominantly dipping north and south (Fig. 3). The majority of these segments dip steeply (40°–90°), with some branches into bedding planes that dip 20°–22°. Many of the individual segments of the Pretorius fault display zones of sintered gouge (cataclasites) with a thickness up to tens of centimeters (lower left in Fig. 3). The cataclasite consists of a green to gray, fine-grained quartzitic matrix with quartz clasts up to the decimeter scale, and it displays structural evidence for granular flow and local melting.

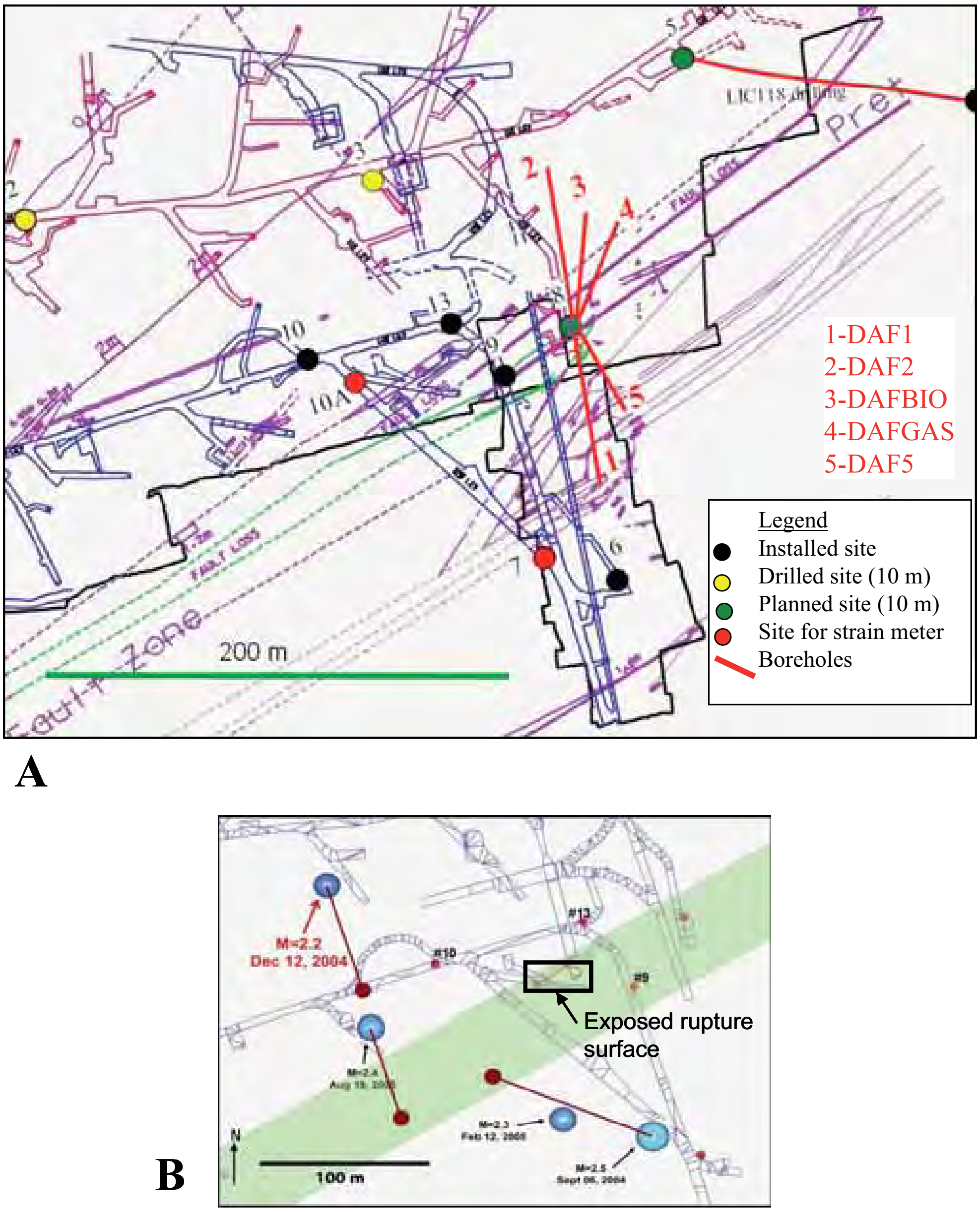

Figure 2. [A] Earthquake laboratory at levels 118–120 of TauTona mine. Tunnels at level 118 (depth = 3.54 km) are marked by red lines; tunnels at level 120 (depth = 3.6 km) are marked by blue lines; wide zone in light green is Pretorius fault zone; thick black line marks margins of mining on both sides of Pretorius fault. Note that while only a small part south of fault has been mined, this part will be mined in next decade; sites marked 2–10 indicate sites of installed or planned system of two 3-D accelerometers, EM sensors and thermistors; Site 8 is laboratory cubby with five inclined boreholes (Fig. 3). [B] Locations of m > 2 events near the laboratory. Original locations marked in light blue circles; preliminary relocations are marked by brown solid circles connected to original location. Note that relocation moves events closer to Pretorius fault.

Building the Laboratory

Our laboratory operations in the TauTona mine this year have focused on the following key items.

1. Drilling through the Pretorius fault zone. A cubby was established within the Pretorius fault zone (Site 8 in Fig. 2A) at a depth of 3.54 km. We drilled five boreholes, all gently inclined and ranging from 17° downward to 25° upward and from 20 to 60 m in length (Fig. 3). One borehole will host an Ishii strain meter. Two boreholes (DAF1 and DAF2, Fig. 3) form a colinear 95-m-long borehole for installing a creep meter. This creep meter will be anchored across the entire fault zone to detect its slip in a wide dynamic range. A fourth borehole (DAFBIO) will be used for *in situ* experiments on microbiological activity, and a fifth borehole (DAFGAS) will be used for continuous monitoring of fault-zone gases.

2. Site characterization. We have characterized the earthquake laboratory site by three-dimensional structural mapping of the ancient Pretorius fault zone and fault segments that were reactivated during recent earthquakes. Five boreholes were logged with a borehole camera for *in situ* stress analysis. Mechanical and chemical laboratory testing will be conducted on samples of rock, gouge, and fluid from the Pretorius fault, as well as on the microbial properties of the cores from the fault zones and adjacent country rock.

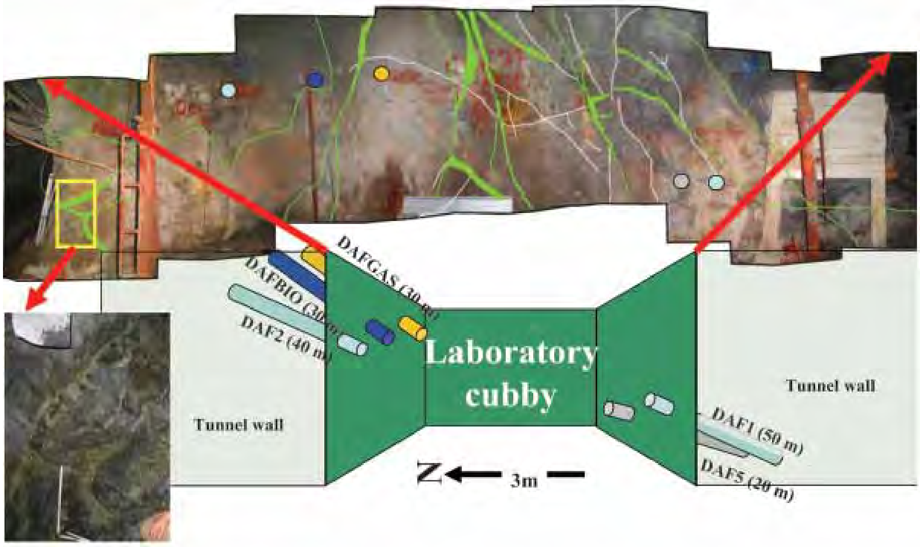

Figure 3. Three-dimensional view into laboratory cubby within Pretorius fault zone in level 118 (site 8, Fig. 2A). Panoramic composite photo (above) displays segments of Pretorius fault filled with sintered cataclasite (light green with detail on lower left). Heads of five boreholes are marked in various colors that correspond to their 3-D presentation in schematic view below.

3. An instrument array (Fig. 2A). When completed by the end of 2006, the laboratory will include a dense array (250-m^2 footprint) of accelerometers (3-D broadband, up to 15 g), seismometers, strain meters, temperature sensors, creep meters, electromagnetic radiation system, and acoustic emissions. Fault-zone fluid chemistry will be monitored with an on-site mass spectrometer after 2006.

Earthquakes and Rupture Zones Along the Pretorius Fault

The network of TauTona mine tunnels was used for three-dimensional mapping of the rupture zone associated with the 2004 earthquake of magnitude 2.2. Mapping was conducted in three interconnected tunnels, one of which was made after the event, and the rupture was traced to a horizontal distance of 40 m (minimum length). Along its entire trace the rupture reactivated three segments of the ancient Pretorius fault (Fig. 4). These segments are quasi-planar, crosscutting segments within the fault zone that carry sintered, metamorphosed Archaean gouge. The reactivated segments strike in east-northeast directions, yet their inclination varies from 21° (a bedding surface) to 90°. Two displaced rock-bolts (Fig. 4C) reveal 10 mm and 25 mm of normal-dextral slip with rake of 23° and 35°, respectively. The rupturing formed fresh, fine-grained, white rock powder almost exclusively along the contacts of the sintered cataclasite and the quartzitic host rock (Fig. 4A). This rock powder is commonly observed in brittle failure in South African mines, and here it appears in one to five thin zones that are each 0.5–1.0 mm thick. Locally, the rupture zone is accompanied by a set of vertical, secondary tensile fractures in the hanging wall (Fig. 4B).

In Situ Stress Field

The bedrock encountered in the TauTona mine is the highly competent quartzites of the Witwatersrand group (uniaxial strength exceeding 200 MPa and Young modulus exceeding 80 GPa). *In situ* stress was determined by analysis of borehole breakouts and drilling induced tensile fractures using images collected with a borehole camera. A slim-hole, 48-mm optical borehole camera (Robertson Geologging) was used to log three vertical boreholes, each ~10 m deep (marked 9, 10, 13, in Fig. 2A, 2B), and two inclined holes, one 418-m-long at 10°–15° inclination (red 5, Fig. 2A) and one 37-m-long at 19° inclination (labeled DAF1, Fig. 2A). It is likely that the 418-m-long hole reflects primarily the ambient, undisturbed tectonic stress, whereas the shorter

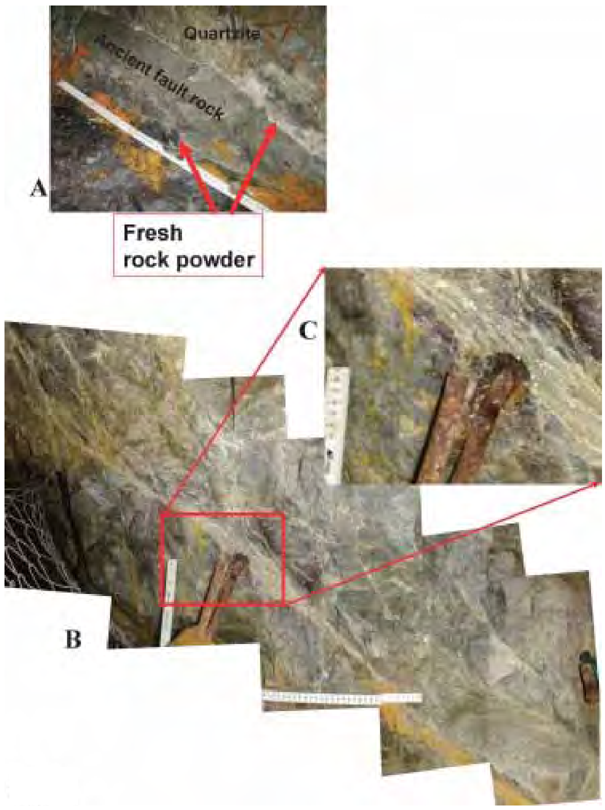

Figure 4. Details of rupture zone of earthquake of magnitude 2.2 of 12 December 2004. Rupture zone location is marked in Fig. 2B. [A] Close-up view of a reactivated segment. [B] A 41° segment with multiple wing-cracks, about five zones of fresh powder and a displaced rock bolt. [C] Close-up view of displaced rock bolt.

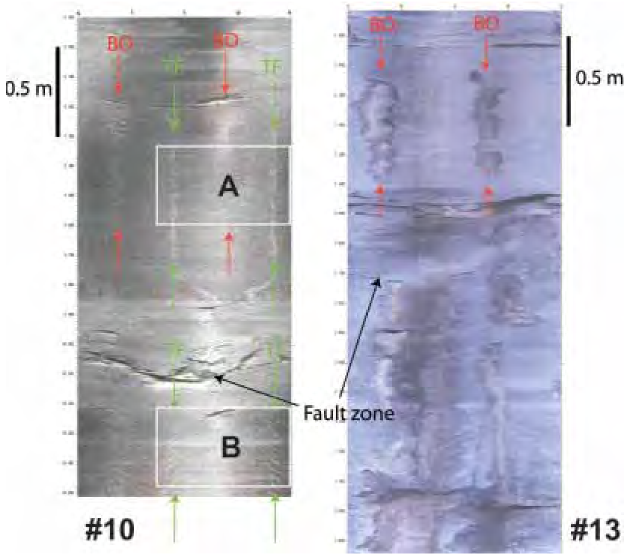

Figure 5. Examples of breakout zones (BO) and drilling induced tensile fractures (TF) from boreholes 10 (left) and 13 (right) in earthquake laboratory area.

holes are strongly affected by stresses induced by the mine infrastructure.

The three short, vertical boreholes lie within the area of the earthquake laboratory (Fig. 2), less than 70 m from the reactivated rupture zone. The images from these boreholes display several zones of breakouts and drilling-induced fractures (Fig. 5). The long borehole (LIC118 hole in Fig. 2) penetrates away from current mining activity. Breakouts were observed for almost the entire logged portion of 418 m, yet no tensile fractures were observed. Four trends of breakouts were detected, and two of them coincide with the location of the Pretorius fault zone.

Anticipated Contributions

Given to the expected proximity of our 3-D dense instrument array to the hypocenters of future earthquakes, the observations to be made during the DAFSAM-NELSAM project are expected to contribute key data on:

- The scales and processes of nucleation, eventual size of the ensuing dynamic rupture, and additional preceding signatures (e.g., geochemical and electromagnetic anomalies, cascading events).
- The detailed properties, dynamics, and energetics of the rupture process (velocity, geometry, crack vs. pulse mode of rupture, dynamic versus geometric sources of heterogeneity, possible opening motion).
- The orientations, magnitude, and heterogeneity of the stress and strain fields in the vicinity of an active fault, and their variations during seismically active and calm periods.
- The Structural, mechanical, and geochemical features related to active fault zones and rupture zones, and their relations to the seismic observations.
- The effects of faulting and earthquakes on the microbiological activity in the fault zone. Do active fault zones host unique communities? Do seismic events increase the microbiological activity or its diversity?

In addition new educational opportunities for American and South African students to improve their understanding of tectonics and structural geologic processes through hands-on involvement with fault-zone mechanics are provided.

Acknowledgements

The DAFSAM-NELSAM project is an international collaboration of dozens researchers from several institutes including University of Oklahoma, U.S. Geological Survey, University of Southern California, Stanford University, Princeton University, ISSI Ltd., TauTona Mine, University of Free State, Council for Scientific and Industrial Research South Africa (CSIR), GeoForschungsZentrum Potsdam, Germany, and Ritsumeikan University, Japan. The TauTona Mine collaborated logistically and financially with DAFSAM in building the earthquake laboratory. Many thanks to the people of AngloGoldAshanti in TauTona mine for their invaluable hospitality and support as well as to Hiroshi Ogasawara of Ritsumeikan University for the collaboration drilling DAF5.

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Related Web Links

http://earthquakes.ou.edu/
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Chesapeake Bay Impact Structure Deep Drilling Project Completes Coring

by Gregory S. Gohn, Christian Koeberl, Kenneth G. Miller, Wolf Uwe Reimold, and the Scientific Staff of the Chesapeake Bay Impact Structure Drilling Project

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Introduction

The Chesapeake Bay Impact Structure Deep Drilling Project (CBIS Project) completed its coring operations during September–December 2005 and April–May 2006. Cores were collected continuously to a total depth of 1766 m. The recovered section consists of 1322 m of impactites beneath 444 m of post-impact continental shelf sediments.

The CBIS Project is a joint venture of the International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS). Project activities began with a planning workshop in September 2003 attended by sixty-three scientists from ten countries. Field operations began with site preparation in July 2005, and coring began in September 2005. Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC) was the general contractor for the drilling operations throughout 2005.

Buried at shallow to moderate depths beneath continental margin sediments in southeastern Virginia, U.S.A. (Fig. 1), the Late Eocene Chesapeake Bay impact structure is among the largest and best preserved of the known impact structures on Earth (Poag et al., 2004). It is the second largest among only a handful of known impact structures that formed in a marine setting, surpassed in size only by the Chicxulub structure on the Yucatan Peninsula, Mexico, the subject of an ICDP drilling project in 2001–2002 (see related Web link at the end of this article).

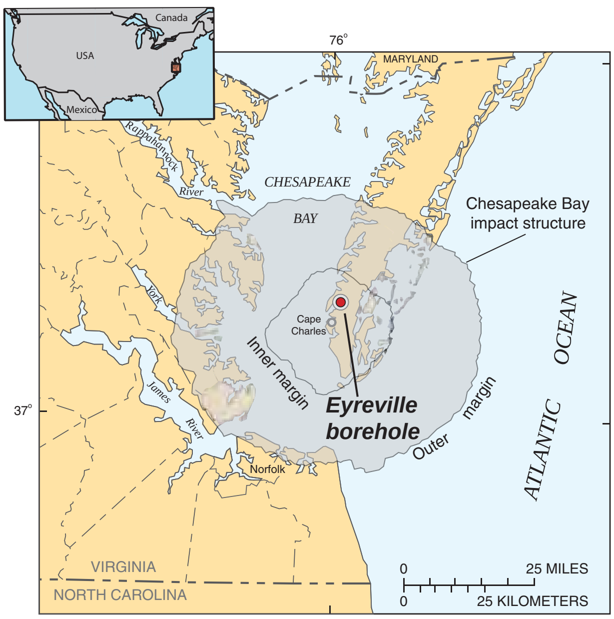

Figure 1. Map showing location of Eyreville drilling site in Chesapeake Bay impact structure.

The Chesapeake Bay impact structure is an inviting target for borehole studies of impact phenomena. This structure is perhaps unique in presenting a drilling target where the effects of an impact on a shallow-marine, rheologically layered, silicic target can be investigated and where the potential exists to recover a complete section of core through the impact-breccia fill of a crater and through the post-impact sedimentary cover. Also, it is the source of one of only four known tektite strewn fields, the North American tektite strewn field (Koeberl et al., 1996).

The Chesapeake Bay impact structure consists of a 38-km-wide, strongly and deeply deformed central zone surrounded by a shallower outer zone of sediment collapse known as the annular trough. Collectively, these two zones have a diameter of about 85 km and a distinctive shape that is generally referred to as an "inverted sombrero" (Fig. 2).

This project also provided an opportunity to study the history of sea-level and climate, the effects of the impact on the regional hydrologic framework and resources, and the ancient and modern microbiota of a deep subsurface environment. The post-impact upper Eocene to Pleistocene sediments that cover the impact structure consist primarily of fine-grained marine sections that document the middle to late Cenozoic sea level history, stratigraphic sequences, and climatic variability of the Mid-Atlantic segment of the eastern U.S. continental margin. The stratigraphic data will be backstripped to account for the effects of sediment loading, compaction, paleowater depth, and basin subsidence. Comparison with results from boreholes outside of the crater (e.g., Miller et al., 2005) will allow us to quantify the effects of tectonics and global sea level.

The presence of salty groundwater throughout the impact structure is of significant interest to hydrologists studying the future availability of fresh water in the densely populated urban corridor located along the south and southwestern margins of the structure. Topics of immediate interest that are addressed by the deep borehole include the physical disruption of the aquifer system by the impact, the entrainment and alteration of Eocene seawater, and the effects of the impact-related hydrothermal system and later diagenesis on groundwater chemistry. The cores were sampled to determine groundwater chemistry and hydrogeologic properties of the sediments and rocks.

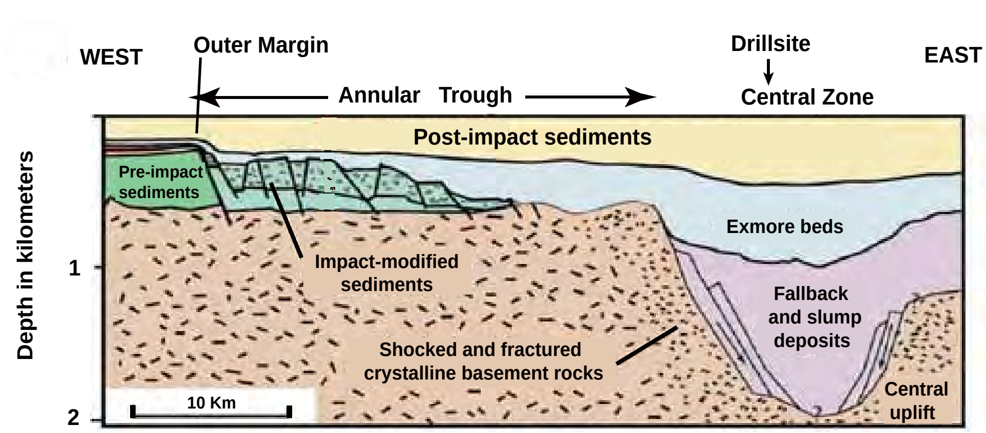

Figure 2. Schematic radial cross section showing half of "inverted sombrero" shape of Chesapeake Bay impact structure. Modified from Horton et al., 2005.

The CBIS Project also provided an opportunity for studying the deep biosphere in a variety of environmental and paleoenvironmental settings to elucidate such basic parameters as subsurface microbial diversity and abundance. The ecology of terrestrial hydrothermal systems related to impact events is essentially unstudied compared to those related to vol-canic activity. The long history of impact cratering throughout the solar system suggests the possibility that impact-related hydrothermal systems might be common habitats on other solar system bodies and highlights the need for studying similar systems on Earth. Cores from the post-impact section provide an opportunity to study fossil microbial traces at significant depths within geologically young marine sediment. Microbiota samples were collected from the three Eyreville cores using appropriate anti-contamination protocols, including halon gas and microbeads as tracers in the drilling mud during core retrieval.

Drilling Strategy

The drilling site is located on private land, known locally as the Eyreville Farm (Fig. 3), in Northampton County, Virginia, about 7 km north of the town of Cape Charles (Fig. 1). The drilling strategy was designed to sample continuously the entire section of post-impact sediments and crater-filling impactites, and a short section of autochthonous breccias in the crater floor, to a depth of about 2.2 km. Problems with lost mud circulation, trapped drill rods, and locally slow penetration rates in the impactite section ultimately limited the total depth to 1.766 km.

Three boreholes were drilled at the Eyreville site (Table 1) in several stages from late July 2005 to early May 2006. Somerset Drilling, Inc. conducted rotary drilling (no coring) to a depth of about 128 m and installed large-diameter steel casing to a depth of 125 m in the Eyreville A borehole. The principal contract driller, Major Drilling America, deepened this borehole to a total depth of 940.9 m using a wireline coring rig. Expanding and sliding red clay sections caused repeated problems during reaming attempts, and the bit eventually deviated from the original hole at a depth of 737.6 m. As a result, duplicate cores were collected between depths of 737.6 m and 940.9 m. The new borehole below the deviation point at 737.6 m was designated as the Eyreville B borehole (Table 1).

Coring proceeded in the Eyreville B borehole to a depth of 1100.9 m, where the bit was deliberately stuck within a section of granite and the drill rods were left in the hole to serve as casing against the red clays. Drilling then resumed in the Eyreville B borehole with a narrower sampling system and continued without major problems to the final depth of 1766.3 m.

Project members from the USGS, Rutgers University, and the Virginia Department of Environmental Quality returned to the Eyreville site in April 2006 and cored a third hole, Eyreville C, to a total depth of 140.2 m (Table 1), using a truck-mounted wireline coring rig. As a result, the upper part of the post-impact sedimentary section was sampled in Eyreville C to complement the deeper section of post-impact sediments recovered in Eyreville A.

Limited suites of geophysical logs such as natural gamma ray, spontaneous potential, and resistivity were acquired from the upper 125 m of the Eyreville A borehole and from the Eyreville C borehole. Unfortunately, planned interim and final geophysical logging activities for the deeper section of the combined A and B boreholes were compromised because of trapped drill rods, logging equipment malfunctions, and bridging of the open hole after the rods were removed. Three logs were acquired after the coring was completed. The USGS logger collected a natural gamma log and a temperature log for nearly the entire length of the combined A and B holes. A temperature log also was collected using a probe

Table 1: Cored sections in Eyreville boreholes.

A:	125.6 to 591.0 m, PQ core (85.0 mm diameter)
	591.0 to 940.9 m, HQ core (63.5 mm diameter)
B:	737.6 to 1100.9 m, HQ core (63.5 mm diameter)
	1100.9 to 1766.3 m, NQ core (47.6 mm diameter)
C:	0 to 140.2 m, HQ core (63.5 mm diameter)

from Karlsruhe University, Germany. Additional temperature logs were collected in the A-B borehole in May 2006 using the Karlsruhe temperature logger. Supplementary measurements of petrophysical properties using a multisensor core logger are planned.

Table 2: Preliminary composite geologic section for Eyreville boreholes (Gohn et al., 2006; Reimold et al., 2006)

0 to 444 m	Post-impact sediments
444 to 1096 m	Sediment-clast breccia and sediment megablocks
1096 to 1371 m	Granitic megablock(s)
1371 to 1393 m	Lithic blocks in sediment
1393 to ~1550 m	Suevitic and lithic breccia
~1550 to 1766 m	Schist and pegmatite; breccia veins

Preliminary Results

The 1322-m-thick section of impactites consists of four major lithologic units (Gohn et al., 2006; Reimold et al., 2006). The lowest unit, probably representing locally brecciated bedrock, consists of about 216 m of mica schist and pegmatite with minor gneiss and a few impact-generated breccia veins (Table 2). About 179 m of suevitic and lithic impact breccias (Fig. 4) overlie the schists and pegmatites and underlie a 275-m-thick megablock, or megablocks, of granitic rock. The upper part of the impactite section (652 m) consists of sedimentary breccia that contains clasts of sediment and crystalline rock. A wide variety of mineralogic, petrologic, geochemical, radiometric, and structural studies of the impactite section are now underway.

The huge unexpected megablock of granite encountered at Eyreville presents an example of challenging decision making during the drilling of large impact structures. The coring of hundreds of meters of granite across numerous days suggested that the crater floor already had been penetrated at an unexpectedly shallow depth according to geophysical data. However, it was decided to continue drilling, and ultimately the base of the granite was reached, below which a section of suevitic breccias was encountered (Table 2), confirming that the block had been transported a great distance during the impact event.

Figure 3. Low-altitude aerial photograph of Eyreville drilling site.

The 444-m-thick section of post-impact sediments consists of Upper Eocene, Oligocene, Miocene, and Pliocene marine sediments and Pleistocene paralic sediments. Lithologic (including grain size, composition, and clay mineralogy), sequence stratigraphic, biostratigraphic (including studies of calcareous nannofossils, foraminifers, dinocysts, diatoms, and pollen), and chemostratigraphic (including Sr isotopes and stable isotopes) studies are ongoing. Preliminary results indicate thick Middle Miocene to Pliocene and Upper Eocene deposits, with relatively thin Lower Miocene and Oligocene sections.

International Sampling Party

The research phase of the project began in March 2006 with an international sampling party. About thirty project scientists from seven countries marked about 1800 samples for future study. Popular targets for sampling were the suevitic and lithic impact breccias and the short section that records the transition from late syn-impact to post-impact sedimentation and biotic-recovery. The cutting and shipping of samples took place from April to June 2006.

Acknowledgements

The planning workshop for the CBIS project was funded by the ICDP and hosted by the USGS. A resulting funding proposal to ICDP was accepted in late 2004, and additional drilling funds were authorized by the USGS. The National Aeronautics and Space Administration (NASA) Science Mission Directorate, the ICDP, and the USGS provided important supplementary drilling funds in November–December 2005 that permitted coring of the deeper part of the impact structure. Studies of post-impact sediments were supported by the U.S. National Science Foundation (NSF), Earth Science Division, Continental Dynamics Program.

We thank DOSECC for their excellent handling of the field operations, and Major Drilling America for their professionalism and the successful completion of the deep coring. We also thank the Buyrn family for the use of their land for the drilling operations and for their enthusiastic interest in the project. We thank the ICDP, the USGS, the NASA Science Mission Directorate, and the NSF for funding the drilling operations. Finally, the principal investigators thank the international group of geologists and technicians for their dedication and hard work at the drilling site.

Figure 4. Suevitic and lithic breccia from Eyreville B borehole.

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Related Web Links

http://chesapeake.icdp-online.org/
http://chicxulub.icdp-online.org/

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Fig. 1 and 2: courtesy of CBIS Deep Drilling Project
Fig. 3 and 4: from David Powars, USGS

Muroto Project: Scientific Drilling of the Late Pliocene Forearc Basin Deposit on the West Coast of Muroto Peninsula, Shikoku, Japan

by Yasuo Kondo, Masao Iwai, and Kazuto Kodama

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The Muroto Peninsula on the Pacific margin of southwest Japan (Fig.1) formed as a result of tectonic events associated with oblique subduction along the Nankai Trough (Sugiyama, 1992, 1994). Late Pliocene forearc basin deposits of the Tonohama Group are exposed on the west coast of the peninsula. Until recently, stratigraphical and paleontological data have been collected only from rather scattered and poorly exposed outcrops (e.g., Yokoyama, 1926; Katto, et al., 1953; Kurihara, 1968; Nishida, 1979; Okumura and Takei, 1993), and no detailed chronological and sequence-stratigraphic framework has been established. The paleoenvironmental changes recorded in the formation thus remain poorly understood.

To overcome these problems, the Muroto Scientific Drilling Project was initiated. It focuses primarily on the Ananai Formation, the uppermost unit of the Tonohama Group. During this project seventy meters of Tonohama sediment core were drilled (Fig.2) in Yasuda-cho, Kochi Prefecture, the type locality of this group. The core covers about two-thirds of the Ananai Formation and overlying terrace deposits. To obtain a general magnetostratigraphic view and to locate polarity boundaries, whole-core measurements were made using a pass-through cryogenic magnetometer located onboard the drilling vessel *Chikyu*. The core then was sampled more densely at portions containing the possible polarity transitions and excursions, and those samples were measured at an onshore laboratory of the Center for Advanced Marine Core Research at Kochi University, Japan. By now the core description is nearly finished, and the density, porosity, and other physical properties were measured with a Multisensor Core Logger.

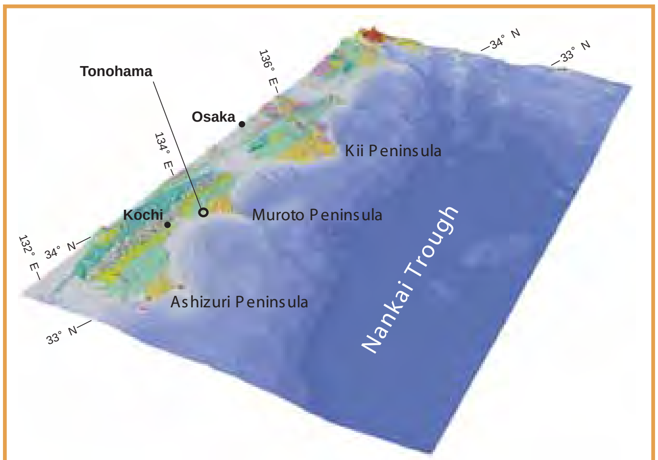

Figure 1. Oblique view of Pacific coast of southwestern Japan and adjacent submarine topography. Map is based on data from Editorial Group for Computer Graphics, Geology of Japanese Islands (2002).

At least seventeen sedimentary cycles are recognized in the core, some of which can be correlated to those identified in surface exposures and confirmed to be transgressive-regressive cycles based on the stratigraphic distribution of mollusks (Kondo, et al., 1997). Also, vertical changes in cycle thickness can be recognized; the cycles tend to become thicker upwards, indicating a general increase of the sedimentation rate in the younger cycles.

An examination of outcrops has shown that transgressive-regressive environmental changes probably originated from glacial to interglacial climatic oscillations (Kondo et al., 1997). To analyze the cycles in detail, a complete stratigraphy needs to be established for the recovered core. This will allow us to reconstruct the habitat distribution and ecology of the fauna and address the relation between composition of the fossil associations and sedimentation rate.

Figure 2. Core operations on a terrace in Tonohama, near type locality of Ananai Formation.

Analysis of the nannofossil assemblages from the contemporaneous strata on the Boso Peninsula (Central Japan) by Kameo et al. (2003) revealed a cooling event at approximately 2.7 Ma and an increased inflow of nutrient-rich surface water that originated from nearshore waters along the East Asian continental margin. This was interpreted to reflect the intensified weathering of the East Asian continent, as related to tectonic and climate processes around the Himalayan-Tibetan Complex and consistent with studies in Lake Baikal (e.g. Müller et al., 2001). Given its location in the southern extension of the Boso Peninsula, the Ananai Formation may contain key strata which help to understand the origin and development of the nutrient-rich surface waters during this period.

Records of paleomagnetic polarity reversals of the core show two normal and three reversed polarity zones with four polarity boundaries representing magnetic transitional zones of 40–60 cm thickness (Fig. 3). Each zone correlates with the Pliocene magnetic polarity time scale, although precise polarity assignment needs independent constraints through micropaleontological and isotope investigations currently underway. The very high resolution magnetostratigraphic record will enable precise age estimation of the Ananai Formation and provide new information on the behavior of the geomagnetic field during transitions of the Pliocene polarity subchrons.

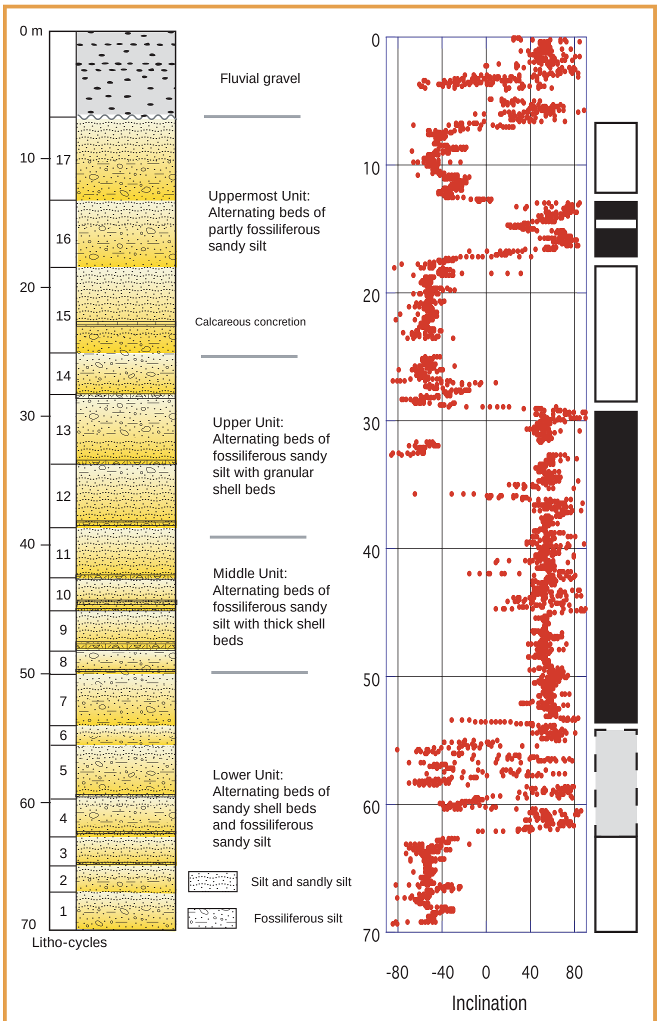

Figure 3. Lithostratigraphy and magnetostratigraphy of drilled core. Lithostratigraphic sequence comprised seventeen sedimentary cycles (left). Magnetostratigraphy with two normal and three reversed polarity zones (right).

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Two Massive Hydraulic Tests Completed in Deep KTB Pilot Hole

by Hans-Joachim Kümpel, Jörg Erzinger, and Serge A. Shapiro

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Introduction

The German Continental Deep Drilling Program (KTB) boreholes in Windischeschenbach, Bavaria, Germany have revealed a wealth of geoscientific data during the years of pre-drilling surveys (1984–1986), the drilling phase (1987–1994), and the subsequent deep-crustal laboratory phase (1995–2000, e.g. Emmermann & Lauterjung, 1997). In 2001, a new series of experiments were launched within and around the two KTB boreholes, the 4.0-km-deep pilot hole (KTB-VB), and the 9.1-km-deep main hole (KTB-HB; Fig. 1). These experiments address the spatial extension of fluid flow and fluid systems in the Earth's crystalline crust, their impact on physical rock parameters, rheology, the dynamics and mechanical stability of the crust, and the transport of soluble matter. Studies of these parameters under *in situ* conditions are of fundamental geoscientific and societal interest in areas such as the optimal use of fluid and thermal reservoirs, the safe disposal of critical wastes, and understanding seismogenesis, particularly in connection with large lake reservoirs.

The use of the KTB site as a crustal laboratory addressing the role of rock fluids is supported by a wealth of exceptional surface and borehole data, two accessible boreholes in crystalline rock, at only 200 m apart, and the occurrence of two distinct, extended fault systems, named seismic reflectors SE1 and SE2, at roughly 7 and 4 km depths, respectively.

The new series of KTB experiments are part of a research program entitled "Energy and Fluid Transport in Continental Fault Systems". The first phase of experiments involved

Figure 1. Aerial view of KTB site with former drill tower atop main hole KTB-HB and pilot hole KTB-VB in center of second light, rectangular area (red circle).

Table 1: Rough schedule of production and injection tests at KTB-VB (neglecting rate changes lasting 100 hours or less); negative rate: injection.

Duration	Rate ($L \cdot min^{-1}$)
21 Jun 2002 – 2 Oct 2002	29
11 Oct 2002 – 23 Oct 2002	29
3 Oct 2002 – 20 Dec 2002	57
7 Jan 2003 – 27 Jun 2003	58
17 Jun 2004 – 17 Jul 2004	-196
9 Aug 2004 – 24 Aug 2004	-186
2 Sep 2004 – 30 Apr 2005	-185

massive hydraulic tests in KTB-VB to probe the SE2 fault system at a depth of 4 km and included a production test and an injection test, with subsequent recovery periods. A second phase of hydraulic tests is currently under planning and is intended to probe the more seismically reflective fault system SE1 at a depth of ~7.2 km.

One-Year Production Test

A production test within Phase I was conducted from June 2002 to June 2003. A submersible pump was lowered to a depth of 1284 m within hole KTB-VB, and 22,300 m^3 of 119°C *in situ* saline fluids were produced from clefts in contact with the open-hole section, at 3850–4000 m depth. An initial production rate of 29 $L \cdot min^{-1}$ (Table 1) resulted in a fluid-level draw down of only 280 m after the first four months, or less than one-third of the expected value. The production rate was therefore doubled for the rest of the test, and the fluid level reached a maximum draw down of 605 m in June 2003. Various geophysical, hydraulic, and geochemical parameters were monitored on-line at the site and were analyzed mostly in real time. Crustal fluids and gases were sampled regularly for detailed geochemical, geobiological, and isotopic investigations. The total volume of produced fluids was about fifty times larger than obtained by the largest previous

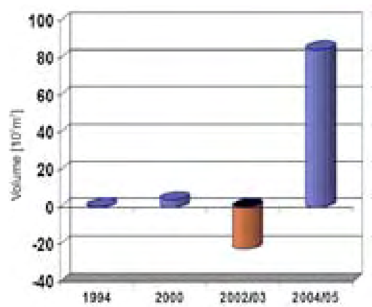

Figure 2. Volume of water mobilized in hydraulic tests at KTB. Tests in 1994 and 2000 were applied to KTB-HB, tests in 2002–03 and 2004–05 to KTB-VB.

pump test in KTB-VB in 1991, and it was less affected by residuals of drilling mud (Erzinger & Stober, 2005).

Specific results of the production test can be summarized as follows. The gas-to-water volume ratio was found to be 0.95–1.05 at surface conditions. Salinity of the formation water is about twice as high as seawater (Möller et al., 2005). Concentrations of most dissolved matter, including gases, were constant throughout the test period. When the fluid production rate was raised, only Ra and Rn concentrations increased because of different scavenging rates from pore and fracture surfaces (Lippmann et al., 2005). Ra and Rn appear to be in radiochemical equilibrium.

Investigations into the chemical and isotopic composition of fluids and gases have given hints to the origin and genesis of crustal gases and fluids. The probable source region is Mesozoic seawater or formation water from Permo-Carboniferous sedimentary rocks of the Weiden embayment, beginning some 10 km southwest of the site (Fehn & Snyder, 2005; Möller et al., 2005). Organic matter suggestive of deep microbial activity was not unambiguously identified.

The hydraulic conductivity of the rocks surrounding the KTB-VB open-hole section is surprisingly high. The bulk hydraulic permeability of the SE2 fault system was found to be 2×10^{-15} m^2 (hydraulic conductivity = 10^{-8} m s^{-1}), about one order of magnitude higher than rocks outside SE2 (Stober & Bucher, 2005; Gräsle et al., 2006; McDermott et al., 2006). The fault system clearly dominates fluid flow on the regional scale. In KTB-HB the fluid level was lowered by about 50 m in response to the fluid withdrawal at KTB-VB. Induced seismicity was not observed during the pump test.

Ten-Month Injection Test

A fluid injection test was conducted from June 2004 until April 2005 following a one-year recovery phase from the production test (Table 1). An electrically powered three-piston pump was operated at the surface to deliver a total of 84,600 m^3 of fresh water into the open-hole section of KTB-VB during the course of the test. Well-head pressure gradually dropped from roughly 120 bar to about 90 bar within the first two months, then slowly increased to 115 bar in April 2005. The total volume injected was twenty-one times larger than during a three-month injection test in August–October 2000 in KTB-HB and 4000 times larger than a short-term injection test at the end of the drilling phase in December 1994 (Zoback & Harjes, 1997; Baisch et al., 2002; Fig. 2).

Again, various geophysical and hydraulic parameters were monitored during the test, and particular attention was given to possible induced seismicity and its relation to pore pressure. Specific results of the injection test and of some of the companion experiments can be summarized as follows. About 3000 micro-seismic events were detected by the

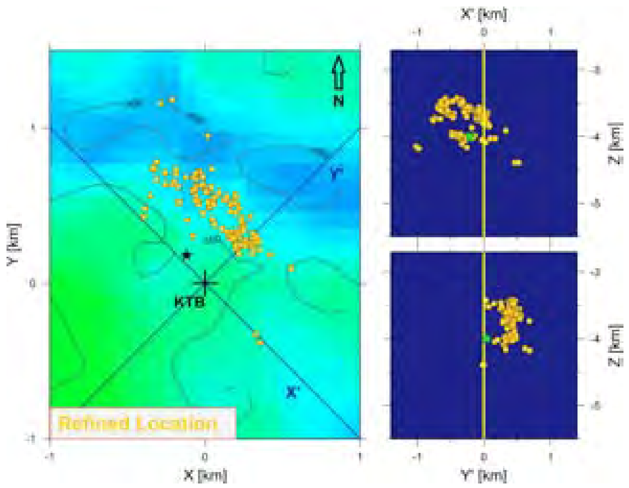

Figure 3. Locations of largest induced seismic events using a refined local 3D velocity model with projections on surface (left) and on X'-Z and Y'-Z planes (right). Asterisk marks bottom hole position of KTB-VB. Coloring on left reflects topography, contour lines indicate elevation in meters above sea level.

borehole geophone in the low-noise environment in KTB-HB, and 150 events were seen by the local seismic network at the surface (Fig. 3). Analysis of those data has revealed that seismicity induced by injecting fluid directly into a crustal fault remains guided by this fault and is triggered by pore-pressure perturbations as low as 0.01–1.00 bar at hypocenters (Shapiro et al., 2006). Most notable was the observation that seismicity started only after injecting a fluid volume approximately equivalent to the amount previously extracted by the pump test into the incompletely saturated formations. The crystalline crust at KTB site was mechanically stable when pore pressure was reduced from its natural level by the pump test, but became transiently destabilized when the re-injection of fluids created a positive pore-pressure perturbation. Pore pressure diffusion ,therefore, appears to act as the dominant mechanism for triggering seismicity.

Given the rather large amount of water that was injected, seismicity generated by this test was much weaker than seismicity induced by the injection tests in 1994 and 2000 in KTB-HB. Obviously, the pressure build-up in 2004–2005 also was much weaker, because the hydraulic transmissivity of the SE2 fault system is much higher than that of the rock formations that took up the injected water during the previous tests.

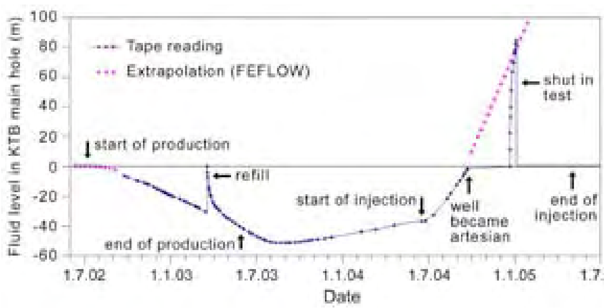

Figure 4. Change of fluid level in KTB-HB in response to hydraulic tests in KTB-VB. FEFLOW-simulation of level change by Kessels, Kuhlmann and Li (personal communication).

The fluid level in KTB-HB rose sharply several days after the injection started in KTB-VB (Gräsle et al., 2006). KTB-HB became artesian in October 2005 (Fig. 4), with an outflow of about 1 $m^3 \cdot day^{-1}$ at the end of the injection test. Since then, both boreholes were kept mostly shut. One year after the injection ceased, the boreholes are still under excess fluid pressure. Hydraulic communication from KTB-VB into KTB-HB actually occurred through a previously identified leakage in the casing of KTB-HB at 5200–5600 m depth (Baisch et al., 2002).

Ongoing and Future Research

We continue to monitor the fluid pressure decay in both boreholes to assess the capability of the faults to recover from the fluid injection. Full recovery of the fluid pressure is not expected before 2008. Other ongoing experiments include push-pull tracer tests in KTB-VB, monitoring of the surface deformation field through borehole tiltmeters of nano-radian resolution (Jahr et al., 2006), and repeated reflection seismics and DC resistivity measurements to map induced changes in reflectivity and electrical conductivity of the SE2 fault system, respectively.

The successful completion of the Phase I hydraulic tests in KTB-VB can answer many of the questions we had in 2001. The plan to conduct hydraulic tests in the SE1 fault system at 7.2 km depth by perforating KTB-HB presents an experimental challenge yet to be overcome in Phase II of this program. Since the seismic signature of SE1 is much more pronounced than that of SE2, new findings are likely on transport properties and the mechanical stability of the crust; however, this would require stopping the leaks in the casing and clearing away equipment lost in the hole.

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Deep Drilling with the ANDRILL Program in Antarctica

by David Harwood, Richard Levy, Jim Cowie, Fabio Florindo,
Tim Naish, Ross Powell, and Alex Pyne

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Introduction

ANDRILL (ANtarctic geological DRILLing) is a new international, multi-disciplinary drilling program that targets geological records that lie hidden beneath the icy blanket of Antarctica. The primary objective is to investigate Antarctica's role in global environmental change over the past sixty-five million years, at various scales of age resolution, and thereby enhance our understanding of Antarctica's potential response to future global changes. Efforts to understand the influence of Antarctica on global climate change require a fundamental knowledge of how the Antarctic cryosphere (ice sheets, ice shelves, and sea ice) has evolved, not only in recent times but also during earlier geological periods when global temperature and atmospheric CO_2 levels were similar to what might be reached by the end of this century. ANDRILL's integrated science approach will use stratigraphic drilling, coring, and multi-proxy core analysis combined with geophysical surveys and numerical modeling to study the Cenozoic history of Antarctic climate and ice sheets, the evolution of polar biota, Antarctic tectonism, and Antarctica's role in the evolution of Earth's ocean–climate system.

The two inaugural ANDRILL projects, McMurdo Ice Shelf Project (MIS) and Southern McMurdo Sound Project (SMS), will be drilled in late 2006 and late 2007, respectively, in the McMurdo Sound Region of the Ross Sea (for science plans, see http://andrill.org), and research on these projects will continue throughout the International Polar Year (IPY, 2007–2008). Funding from Germany, Italy, New Zealand, and the United States supported the development of a new dedicated drilling system and drilling camp for ice-based operations. The anticipated twenty-year lifespan of the drilling rig is expected to enable future drilling in other regions of the Antarctic margin. Future ANDRILL projects will depend on new proposals to national funding agencies. ANDRILL is managed through the McMurdo-ANDRILL Science Implementation Committee (M-ASIC) and the ANDRILL Operations Management Group (AOMG), whose directions are implemented through the Science Management Office (SMO) at the University of Nebraska-Lincoln and the Project Operator's Office within Antarctica New Zealand, respectively. Ongoing and future community involvement, proposal development, and site characterization are encouraged, facilitated, and coordinated by the ANDRILL Science Committee (ASC) and the SMO.

The Drilling System

The newly built, state-of-the-art ANDRILL drilling system is based on technology proven during the Cape Roberts Project (1995–2000) and has the capability to recover soft sediment and rock strata from more than 1000 m below the seafloor in 1000 m of water (Fig. 1). Its narrow-kerf, high-speed, diamond-coring system enables high-percentage (>90%) core recovery. The ability to use either fast ice or shelf ice as a drilling platform allows sampling from a wide range of marine environments. The design, engineering, construction, and operational expertise are contracted by Antarctica New Zealand from Victoria University of Wellington and Webster Drilling of New Zealand. The rig underwent testing in Canterbury, New Zealand in late 2005 (Fig. 2) before it was shipped to Antarctica and reassembled near Scott Base in early 2006 (Fig. 3).

The ANDRILL drilling system is based around a mining-type drilling rig constructed by UDR in Brisbane, Australia, but it has been customized for ANDRILL scientific requirements and for Antarctic conditions. Customization includes (1) reconfiguration of the main winch for a double line pull to deploy sea-riser casing, which weighs up to thiry tons; (2)

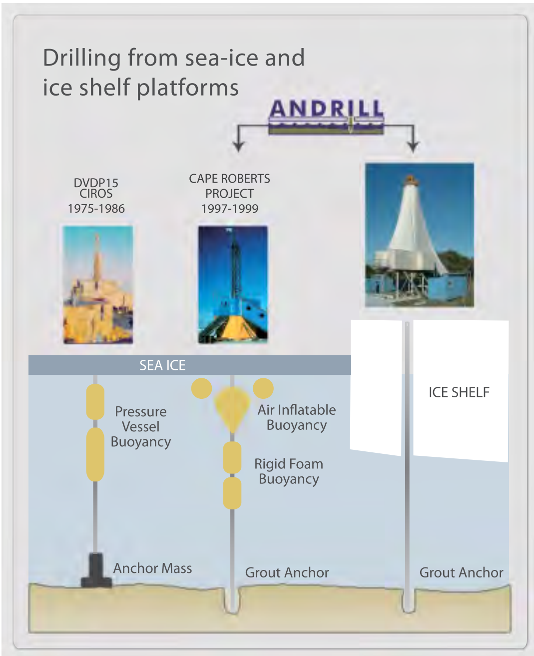

Figure 1. Drilling system development and operational setting for ANDRILL on floating sea-ice and ice shelf.

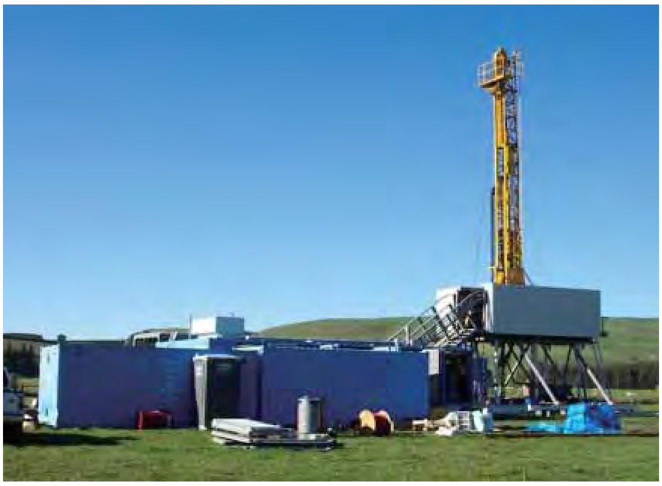

Figure 2. Testing ANDRILL rig in Canterbury, New Zealand (October 2005) before shipping south to Antarctica.

heave compensation to allow for up to 1.5 meters of vertical tidal movement of the ice shelf or sea-ice platform, (3) enclosure to provide a warm environment for workers and equipment on the drill floor, and (4) separation of the rig hydraulic power pack (in an insulated container) and the drill mast and winches to provide the best heated location. The entire system can be broken down into components that can be airlifted or transported on sledges. Some parts of the system, such as the drilling platform and catwalk, have been designed and fabricated to incorporate sledge bases for easy transport across snow and ice (Table 1).

Science Plan

During the austral summers of 2006 and 2007, ANDRILL will drill from an ice-shelf platform for the MIS Project and a sea-ice platform for the SMS Project in the McMurdo Sound region to obtain new information about the Neogene Antarctic cryosphere and the evolution of Antarctic rift basins. The McMurdo Sound region was selected for the first phase of ANDRILL for scientific and logistical reasons. McMurdo Sound is located at the juncture of several components of the West Antarctic Rift System, including the Victoria Land Basin, Transantarctic Mountains, and Erebus Volcanic Province (Fig. 4). This region is also situated near the confluence of several components of the Antarctic cryosphere, including the East and West Antarctic ice sheets, local alpine glaciers, and sea ice. As proven by Cape Roberts drilling, proximity to the Transantarctic Mountains combined with ample accommodation space from tectonic subsidence of the Victoria Land Basin gives the region excellent potential to produce high-quality, time-continuous paleoenvironmental records, during times of both large and small Antarctic ice sheets. In some areas of McMurdo Sound, Neogene volcanism has produced flexural-moat basins superposed on the Victoria Land rift basin. The flexural moats provide an ideal setting for sediment accumulation and a means of developing a high-resolution chronology from volcanic detritus. The MIS and SMS drilling sites are based on geophysical and seismic surveys combined with knowledge gained at other nearby drilling sites. Both study areas are located to maximize the potential recovery of new stratigraphic records.

Table 1. Components of the drilling system include:

- drill rig and the drill platform
- the catwalk sledge & rod ramp, providing staging area for the sea riser and drill pipe
- the drill fluids (mud) system, providing a fluid for cooling the drill bit and lifting drill cuttings from the base of the hole
- the cementing system, which can supply cement to anchor the sea riser to the sea floor, case or plug off the hole
- the hydraulic power system, which supplies the drill rig, and two electrical generators
- the hot water drilling system, which will keep an open hole around the sea riser pipe

The scientific objectives of these two inaugural ANDRILL projects are as follows: (a) to document the initial onset and subsequent history of sea-ice presence or absence, (b) to document the evolution and demise of Neogene terrestrial vegetation, (c) to establish a local Late Neogene sea-level record, (d) to test whether stable, cold-polar climate conditions persisted for the last 15 M.y., (e) to construct a composite history of glacial and interglacial events across a coastal to deep basin transect, (f) to provide chronostratigraphic control for the regional seismic framework in the Victoria Land Basin and western Ross Sea, (g) to develop a Neogene subsidence and fault history for the Victoria Land Basin, and (h) to feed new paleoclimatic data into ice-sheet and climate models.

The main goal of the McMurdo Ice Shelf Project (MIS) is to determine past ice-shelf responses to climate forcing, including variability at a range of timescales. One borehole in approximately 900 m water depth will sample a 1200-m-thick body of Plio-Pleistocene glaciomarine, terrigenous, volcanic, and biogenic sediment within the Windless Bight region of a flexural moat basin surrounding Ross Island. The MIS Project is led by Co-Chief Scientists Tim Naish and Ross Powell.

Figure 3. Attaching drilling rig mast to jack-up platform after off-load in McMurdo. Assembly of ANDRILL System at ice edge near New Zealand's Scott Base.

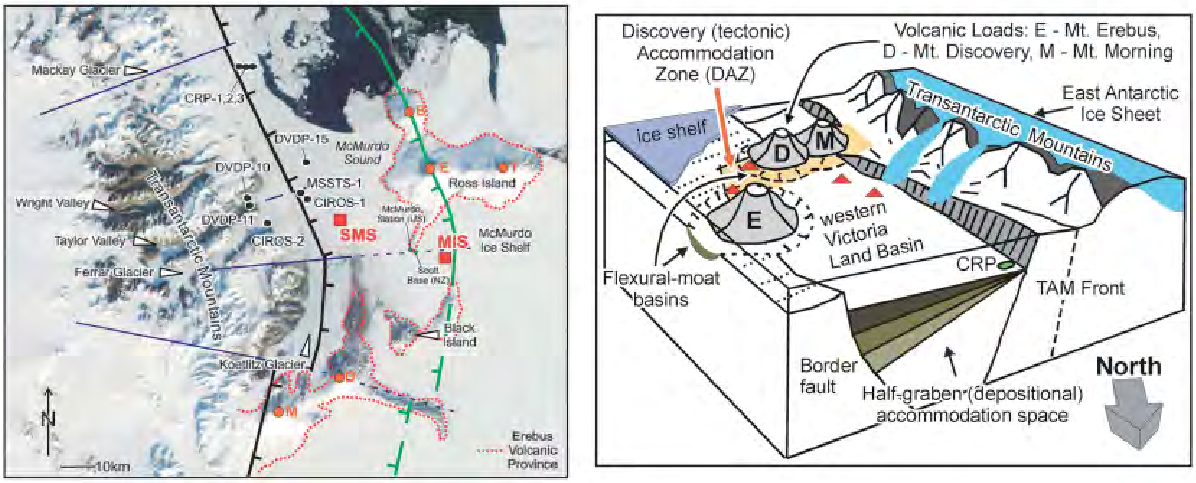

Figure 4. *Left:* McMurdo Ice Shelf (MIS) and Southern McMurdo Sound (SMS) Projects (red squares) are scheduled for drilling during 2006 and 2007 austral summers, respectively. Also shown are locations of previous stratigraphic bore holes (DVDP, CIROS, MSSTS, and CRP) in McMurdo Sound region. *Right:* Schematic stratigraphic and structural cartoon of Victoria Land Basin shows development of accommodation space within half graben. Neogene volcanoes of Erebus Volcanic Province have progressively depressed crust forming flexural-moat basins that trap an expanded Neogene sediment history.

The main goal of the Southern McMurdo Sound Project (SMS) is to establish the history of Neogene Antarctic ice-sheet variation and longer-term climate evolution. One borehole of more than 1000 m depth below seafloor in 530 m water depth will sample a sequence of strata identified on seismic lines and inferred to represent a middle Miocene to upper Miocene sequence of seismic units that expand basinward and are overlain disconformably by Pliocene and Pleistocene strata. This borehole will penetrate strata that lie stratigraphically above the lower Miocene section recovered at the top of the sequence drilled by the Cape Roberts Project. The SMS Project is led by Co-Chief Scientists David Harwood and Fabio Florindo.

The selected drilling sites lie close to existing Antarctic logistical centers, including McMurdo Station (U.S.) and Scott Base (New Zealand), thus minimizing the logistical difficulties associated with operating a new drilling system in an extreme environment. The Crary Science and Engineering Center (CSEC or Crary Lab) at McMurdo Station is a state-of-the-art science facility in which most of the on-ice scientific analyses will occur, and access to Crary Lab allows ANDRILL to involve a full scientific team to achieve comprehensive on-ice core characterization and analysis. Other research will be conducted during drilling and at the home institutions of the science team members. Approximately one hundred scientists, students, educators, technical assistants, and drilling team members will be involved in each project, on and off the ice. The ARISE Program (ANDRILL Research Immersion for Science Educators) will bring six educators to Antarctica as members of the science team for both projects to develop further a set of diverse and effective education and outreach materials with a polar content for the IPY and beyond.

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Submitted by David Harwood and Richard Levy on behalf of members of the M-ASIC and AOMG committees, the staff of the ANDRILL Project Operator within Antarctica New Zealand, the staff of the Science Management Office at the University of Nebraska-Lincoln, and the staff of the Antarctic Research Centre of Victoria University of Wellington. Members of these ANDRILL bodies are identified at the new Web site for ANDRILL (http://andrill.org), which can be visited for more information. The SMO is supported by a grant from the U.S. National Science Foundation.

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Related Web Links

http://andrill.org
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Figure Credits

Fig. 2: photograph by Alex Pyne.
Fig. 3: photograph by Tim Naish.

The Micropaleontological Reference Centers Network

by David Lazarus

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Introduction

The Micropaleontological Reference Centers (MRCs) comprise large microfossil slide collections prepared from core samples obtained through the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). The MRCs have been maintained for three decades, largely as a volunteer effort by a global network of curators at more than a dozen institutions (Fig.1, Table 1). They were originally intended to provide a permanent micropaleontological archive for the DSDP; however, as their geographic and stratigraphic coverage has increased they have become increasingly valuable for research and teaching. This article describes the MRCs and their current usage, identifies the need to maintain and improve the accuracy of the microfossil taxonomy upon which most DSDP and ODP geochronology is based, and cites the potential for the future use of the MRCs by the Integrated Ocean Drilling Program (IODP).

Distribution and Content

The MRCs consist of eight identical sets of slides for four microfossil groups. The institutions that hold these sets provide space, microscopes, and other facilities to users of the collections, and many of the institutions contribute to the development of the MRC collections by assisting with sample selection and preparation.

Currently, the MRCs hold nearly 20,000 prepared slides for planktonic foraminifera, calcareous nannofossils, radiolarians, and diatoms. These four groups are the dominant source of biostratigraphic data for DSDP, ODP, and IODP deep-sea sediment cores. The MRC sampling strategy has always aimed at achieving comprehensive coverage for each fossil group for late Mesozoic to Recent time intervals and all oceanic regions. Samples from more than one thousand individual boreholes have provided near global, albeit non-uniform coverage, extending in some cases back to the Jurassic (Figs. 2–4). Geographically, mid-latitude central gyre regions are under-represented, particularly in the Pacific, and many more samples are available from the younger time intervals.

Research Opportunities

One general use of the MRC collections is to provide an overview of how well scientific ocean drilling has sampled the geologic record of the oceans. The patterns of recovery shown in Figures 2, 3, and 4 reflect past programmatic drilling decisions as well as the primary nature of sediment preservation in the ocean. The stratigraphic distribution of MRC samples illustrates the well-known power-law correlation of relative sediment abundance versus geologic age, and the effects of differential preservation and evolutionary change are also reflected in the relatively lower abundances

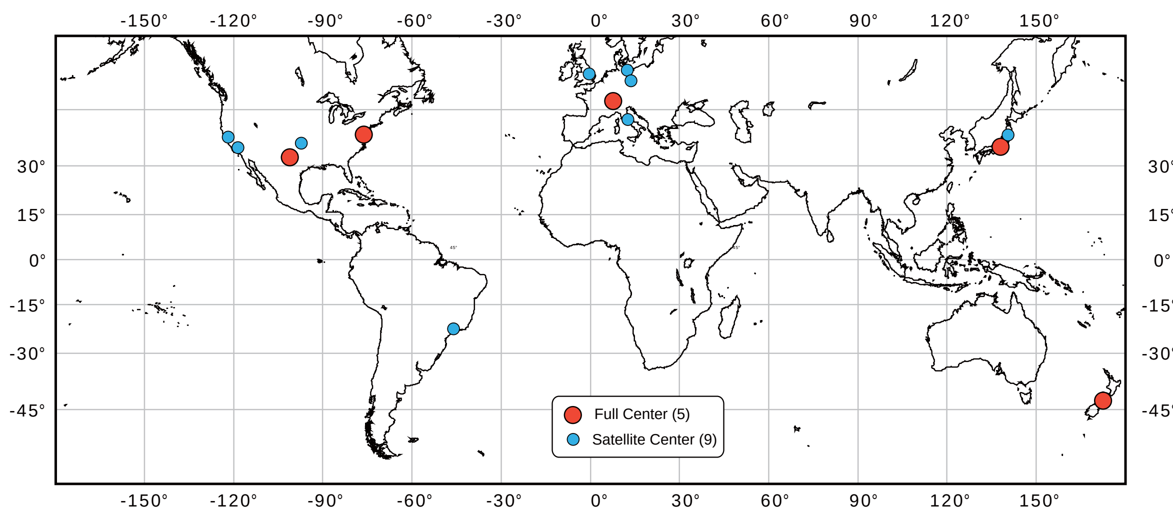

Figure 1. Locations of MRC collections. Full centers (red) hold slides for all four fossil groups. Satellite centers (blue) generally hold slides only for a single fossil group.

Table 1: Locations of MRC collections. Full contact information can be found at http://iodp.tamu.edu/curation/mrc/institutions.html

Collection	Host Institution	City	Country
Full MRCs			
Full Collections	National Science Museum	Tokyo	Japan
Full Collections	GNS Science	Lower Hutt	New Zealand
Full Collections	Natural History Museum	Basel	Switzerland
Full Collections	IODP USIO	College Station, Texas	U.S.A.
Full Collections	Museum of Natural History	Washington, D.C.	U.S.A.
Satellite MRCs			
Foraminifera	Federal University of Rio de Janeiro	Rio de Janeiro	Brazil
Radiolaria	Museum für Naturkunde	Berlin	Germany
Foraminifera, Radiolaria	Universität Bremen	Bremen	Germany
Calc. Nannofossils	Universitá degli Studi di Parma	Parma	Italy
Radiolaria	Utsunomiya University	Utsunomiya	Japan
Diatoms, Foraminifera	Institute of the Lithosphere	Moscow	Russia
Calc. Nannofossils	The Natural History Museum	London	U.K.
Radiolaria	Scripps Institution of Oceanography	La Jolla, Calif.	U.S.A.
Calc. Nannofossils, Diatoms	University of Nebraska	Lincoln, Neb.	U.S.A.
Diatoms	California Academy of Sciences	San Francisco, Calif.	U.S.A.
Calc. Nannofossils, Diatoms	Florida State University	Tallahassee, Fla.	U.S.A.

of siliceous microfossils, particularly diatoms, in Paleogene and older sediments. Such important information is readily available from the MRCs for planning future scientific drilling priorities and documenting the strengths and weaknesses in global coverage for different time intervals. As an example, the MRC collections show clearly how few deep-sea sediment samples, particularly those with siliceous microfossils, have been recovered so far for the early Paleogene, let alone the Mesozoic.

The MRC collections are also used regularly in individual research projects, with several dozen studies by curators and visitors recorded in 2004 (Fig. 5; the most recent year with compiled information available). For example, Funakawa and Nishi (2006) recently examined numerous MRC slides to determine the biogeographic affinities of nearly one hundred Paleogene radiolarian species, and they applied this information to decipher the development and spread of Antarctic water masses across the Eocene-Oligocene transition. Whereas early studies of evolutionary patterns over time were based on data from a small number of sections, more recent research in paleontology has made use of larger databases of fossil occurrences. Analyses of the Sepkoski database and its successor Paleobiology Database PBDB have yielded many valuable scientific insights, such as the importance of catastrophic extinction in the evolution of life on Earth (e.g., Lane et al., 1997). Micropaleontologists are only now beginning to conduct similar global syntheses of their data to understand how plankton diversity has evolved, responded to, and influenced climate change. Recent examples of such syntheses include an analysis of the oceanographic factors controlling recent planktonic foraminifera diversity (Rutherford et al., 1999), based on the archive of global plankton distributions created by CLIMAP (Climate: Long range Investigation, Mappping, and Prediction), and an analysis of global trends in Cenozoic diatom evolution (Finkel et al., 2005), which utilized the Neptune database of global DSDP and ODP microfossil occurrence data. Studies of previously published data are limited, however, by different priorities in measurement methods, heterogeneity of data quality, and gaps in coverage. Ultimately, new sets of systematically collected global micropaleontology data will be needed to address many important questions about longer-

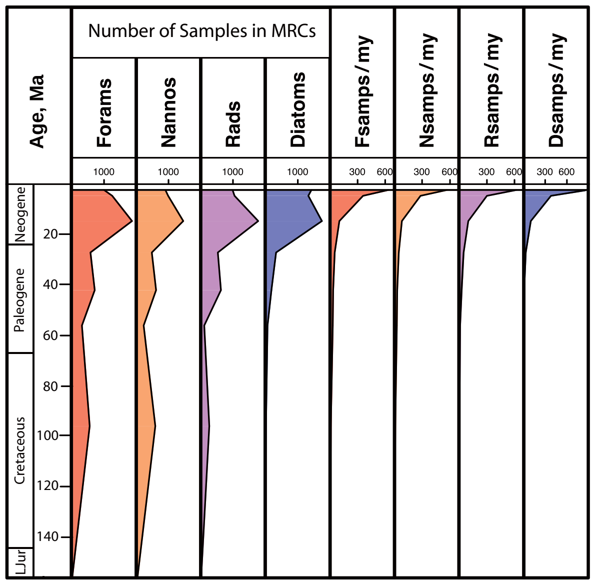

Figure 2. MRC samples vs. age, by geologic time interval. Absolute numbers in four columns on left are normalized to time interval for four columns on the right based on ages in MRC database (variable sized bins reflecting sample size—Cenozoic by epoch, Mesozoic by period).

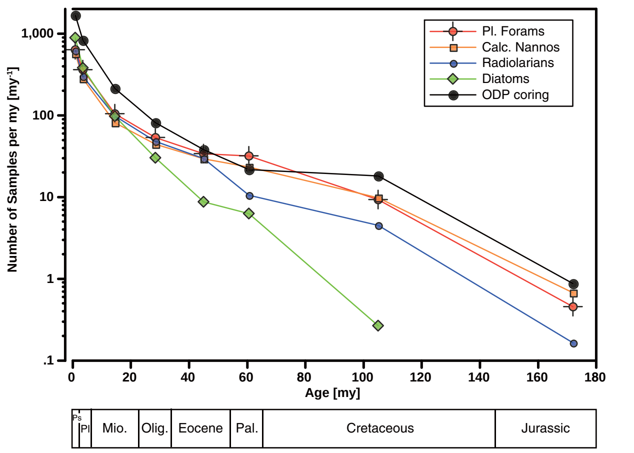

Figure 3. Number of MRC samples / my vs. age interval, log plot and summary of ODP core recovery by age. Core information was derived from preliminary Initial Reports data set covering Legs 101–159 only, courtesy of ODP.

term patterns of microfossil evolution and paleoceanography. The MRCs, with their global sample coverage, represent an excellent source of ready-made materials for such studies, particularly if augmented with additional sampling of newly recovered materials from older time intervals.

Maintaining Accuracy of Older Age Data

Accurate geologic age estimates are essential for many aspects of scientific ocean drilling and other geoscience research. Age models based on time series of physical or chemical parameters and advanced methods like orbital tuning have revolutionized high-resolution chronostratigraphy, but these more-sophisticated methods still depend on a basic age-stratigraphic framework almost always provided by biostratigraphy. The concepts and definitions of species, however, continue to evolve as more morphologic, molecular, and stratigraphic data become available. As these definitions change, our ability to link old and new definitions becomes increasingly frayed. It might come as a surprise to non-specialists that many species concepts, though normally adequately documented when first defined, are not yet readily available in a single authoritative place but are instead spread throughout a large body of not always easily accessible literature. This means that we have difficulty linking older DSDP and ODP data to new data sets. This can become a serious problem because the biostratigraphic data and the age models based on them become increasingly difficult to update.

Teaching and Training

The MRC collections are also used for teaching in primary, secondary, and post-secondary education, and they provide an opportunity to train micropaleontologists prior to an ocean drilling expedition. One long-term concern identified by the paleontology working group of the IODP Scientific Technology Panel (STP) is the continued decline in the pool of taxonomic specialists required to conduct primary biostratigraphic dating of sediments recovered by scientific ocean drilling. This decline in taxonomic expertise is part of a more general trend of reduced training in taxonomic specialties in the biological sciences, but the IODP must address this issue if it wants to ensure the future availability of high-quality biochronologic data. The MRCs have already played a minor, ad hoc role in providing pre-assembled sets of suitable microfossil material to train individual scientists prior to cruises. This activity could, and perhaps should, be increased substantially in the future. One such example, made from MRC materials for shipboard use, already exists for Cenozoic tropical radiolarian stratigraphic forms (Nigrini and Sanfilippo, 2001).

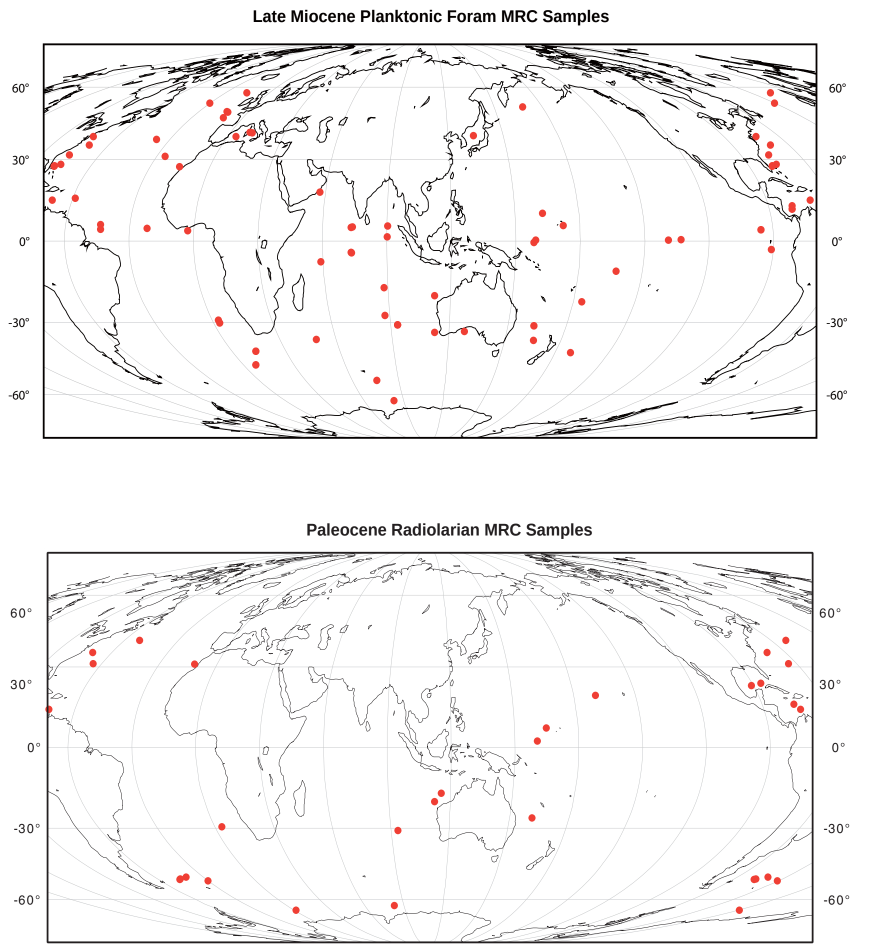

Figure 4. Location maps of MRC samples for selected time intervals. Late Miocene time interval is only half as long as Paleocene. Note: to show full Pacific basin, eastern Atlantic (and data plotted there) is duplicated on right edges of maps.

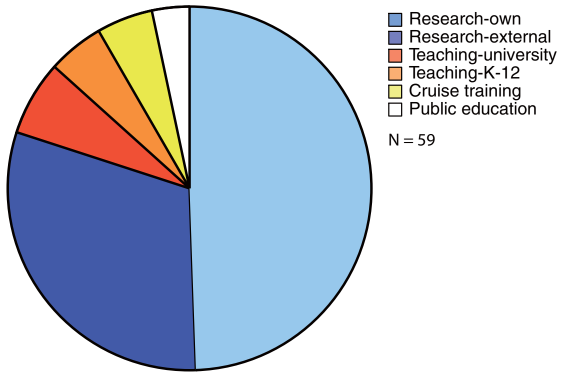

Figure 5. MRC usage in 2004, based on MRC curatorial reports.

Digital Taxonomic Dictionaries

The MRC collections can, and indeed originally were conceived to, assist in combating the above problem by providing representative specimens of biostratigraphically important microfossils from older sedimentary sections. These specimens can be examined when necessary to determine how newer taxonomic definitions map onto older materials and thereby maintain an adequate degree of uniformity in the definition of age-significant biostratigraphic data.

Now the time has come to improve substantially the community efforts to review properly and document existing species concepts in a way that they can be used as a reference standard for all IODP micropaleontology data. A lack of convenient access to taxonomic descriptions will negatively impact the IODP and ocean sciences by undermining the training of a new generation of specialists and making the re-analysis and updating of older biostratigraphic data more difficult and error-prone. The MRCs and the broader micropaleontologic community ought to meet this challenge by coordinating the development of digital taxonomic standard dictionaries, drawing on the global collections of material prepared directly from DSDP, ODP, and IODP samples. The community has already begun a dialog that could lead to major progress in this field. Scientists interested in using the MRC collections for research or assisting in the further development of the collections should visit the MRC Web page at http://iodp.tamu.edu/curation/mrc.html and contact the author or the nearest MRC curator (Table 1).

Acknowledgements

The author thanks the many colleagues who have volunteered their time and resources over the last thirty years to create the MRC collections. I also thank Annika Sanfilippo and Bob Goll for comments on this manuscript.

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Related Web Links

Main MRC web page:
http://iodp.tamu.edu/curation/mrc.html

An example of MRC based training data and linked set of prepared slides is available for Nigrini, C. and Sanfilippo, A., 2001 reference:
http://www-odp.tamu.edu/publications/tnotes/tn27/

Neptune database and NSF sponsored planktonic foraminifera DTD:
http://www.chronos.org

Example of a community supported DTD:
http://www.radiolaria.org

An Overview of IODP Scientific Publications

by Emanuel Soeding, Dan Evans, Ann Klaus, Shin'ichi Kuramoto, Hans Christian Larsen, and Angie Miller

doi:10.2204/iodp.sd.3.11.2006

Development of IODP Reports and Publications

A new series, the *Proceedings of the Integrated Ocean Drilling Program*, is continuing the legacy of scientific ocean drilling publications that began with the *Initial Reports of the Deep Sea Drilling Project* and the *Proceedings of the Ocean Drilling Program*. Together, these series document almost forty years of ocean drilling expeditions.

In 2004, the format of the *Proceedings of the Integrated Ocean Drilling Program* was defined based on input from the ocean drilling scientific community, the Integrated Ocean Drilling Program (IODP) Implementing Organizations, scientific publishers, and program management (IODP-MI). The IODP scientific publications structure comprises a report series, a *Proceedings* series, and the program journal *Scientific Drilling* (Fig. 1). The new IODP publication structure is, except for the journal, exclusively electronic and offers easy Web access (http://www.iodp.org/scientific-publications/). Another important element is the program decision to pursue publication of scientific papers related to post-expedition research in the open, peer-reviewed literature.

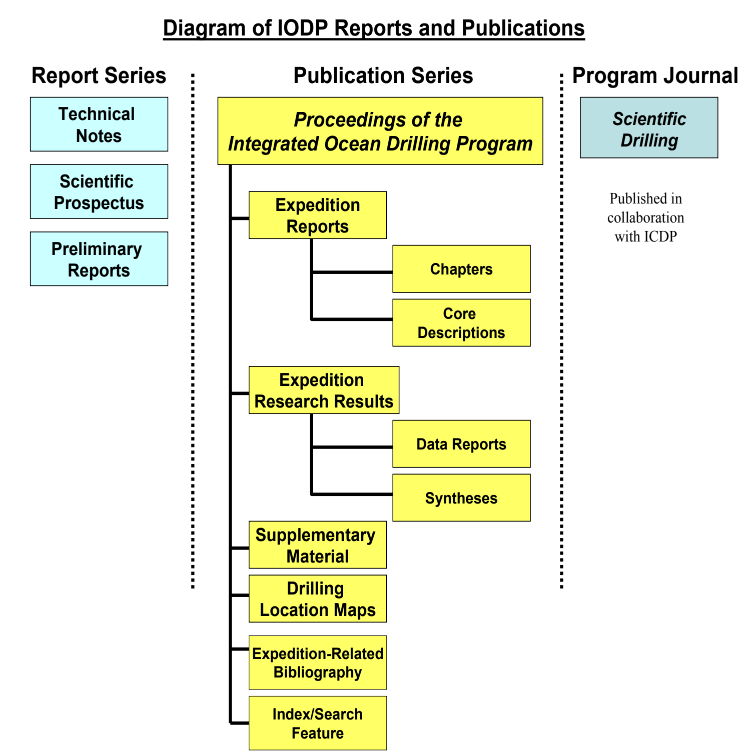

Figure 1. Publication structure in IODP consisting of the report series, publication series, and program journal *Scientific Drilling*.

IODP Reports

The IODP report series comprises *IODP Scientific Prospectus*, *IODP Preliminary Report*, and *IODP Technical Notes*. The *Scientific Prospectus* outlines the expedition plan and is published no later than two months before an expedition. The *Preliminary Report* summarizes the expedition technical operations and scientific results and compares the expedition achievements to the expedition goals outlined in the *Scientific Prospectus*. The *Preliminary Report* is prepared for publication within two months after the conclusion of an expedition. *Technical Notes* documents program-related scientific and engineering operational documentation and is published on an as-needed basis.

IODP *Proceedings*

The *Proceedings of the Integrated Ocean Drilling Program* is a serial publication that contains a detailed summary of expedition technical operations and scientific results and related peer-reviewed data reports and synthesis papers that cover post-expedition research. A single *Proceedings* volume will be published for each IODP expedition or drilling project (a series of related expeditions). Each volume is divided into two main sections—"Expedition Reports" and "Expedition Research Results." The Expedition Reports section contains a record of the expedition objectives, a thorough summary of the scientific and engineering results, and core description data and is published on the Web in HTML and PDF formats and on DVD (Fig. 2) at the end of the sample and data moratorium period. The Expedition Research Results section will contain peer-reviewed data reports and synthesis papers based on post-expedition research. In a change from the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP), all other scientific papers documenting IODP post-expedition research results will be published in peer-reviewed English language journals. To ensure that the IODP continues to obtain a compendium of expedition-related work, each *Proceedings* volume also includes a bibliography of

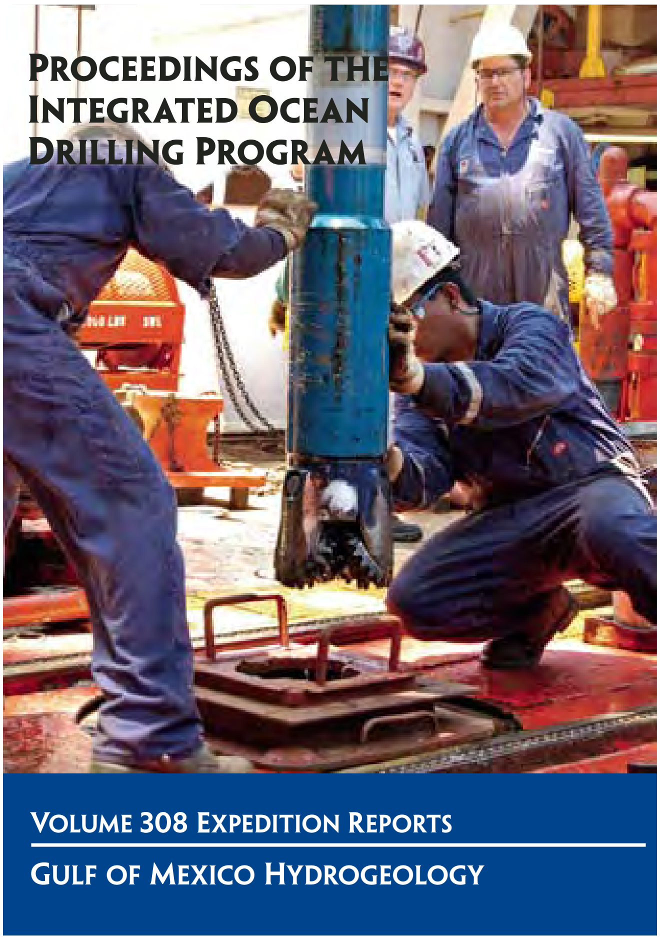

Figure 2. Cover of Volume 308 DVD of *Proceedings of the Integrated Ocean Drilling Program* published in 2006.

references from expedition-related publications. Readers can also link to abstracts and papers that are published electronically in open-access journals. Maps of expedition drilling sites and supplemental data in proprietary formats other than PDF and ASCII are also included in the *Proceedings*. Each volume will be completed three years after the corresponding sample and data moratorium.

Scientific Drilling

The journal *Scientific Drilling* is published by IODP jointly with the International Continental Scientific Drilling Program (ICDP) to broaden the impact of IODP scientific results, forge a partnership with the ICDP, and establish a common source of information for all scientific drilling. The journal accepts brief scientific contributions on any aspect of scientific drilling—land, sea, lake, or ice— including borehole instrumentation and long-term observatories. A key element of the journal is brief summary articles or progress reports from all IODP and ICDP expeditions and projects. *Scientific Drilling* is issued in print and online in PDF format twice a year, with publications scheduled in March and September.

Developments

IODP scientific publications incorporate Web-based information technology that increases reader access and allows a stronger integration of text-based publications and data objects in distributed data repositories. The IODP has joined CrossRef to register digital object identifiers (DOIs) for all IODP scientific reports and publications. The DOI system improves accessibility to scientific publications and provides a method for member publishers to cite and link to each others' online publications. To further improve access to IODP-related research, The IODP will work with publishers to provide open access to publications that contain results from IODP data. The program is also taking steps to further integrate publications with program-generated data as well as data from other related programs through the Scientific Earth Drilling Information System (SEDIS). Proposed enhancements in SEDIS Phase 2 include advanced search tools for both text and data (Miville et al., 2006). As the IODP moves forward implementing new techonology, the ODP reaches back to secure the legacy of multiple decades of scientific ocean drilling through an exciting initiative to digitize the printed *Initial Reports of the Deep Sea Drilling Project* series and the early volumes of the *Proceedings of the Ocean Drilling Program* series. These volumes will be available online in PDF format in 2007–2008 with text-searching capability. For further information please contact: publications@iodp-mi-sapporo.org.

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Drilling Vessel *Chikyu*: Status, Capabilities, and Current Operations

By Daniel Curewitz, Shin'ichi Kuramoto, and Yoshi Kawamura

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Background and History

The Deep Sea Drilling Vessel *Chikyu* is a state-of-the-art drilling platform that can reach geological targets previously inaccessible to scientific drilling. This 210-m-long, 57,000-ton vessel comes equipped with a 121-m-tall drilling derrick, a fully integrated riser drilling system and blow-out preventer (BOP), and a highly automated drill floor system that runs efficiently and safely with a small number of operating personnel. The *Chikyu* is flexible enough to allow both riser and riserless operations, depending on the scientific and technical requirements of a given expedition.

Construction of the *Chikyu* finished in July 2005 in Nagasaki, Japan, and the ship set sail in early August 2005 (Taira, 2005). Basic operational tests, vessel operation training, and safety protocol and procedure training were conducted off Nagasaki, in Suruga Bay, and off the Boso Peninsula, Japan. Several open-house events were scheduled around Japan during this period, and more than 25,000 visitors gained a first-hand view of the *Chikyu*'s scientific capabilities. In October 2005, full-scale test operations were conducted off the Shimokita Peninsula between Honshu and Hokkaido, Japan (Fig. 1). These operations were designed to train the vessel operators, scientists, navigators, and drilling and technical crew; to troubleshoot and modify the drilling, coring, and laboratory systems; and to provide a basis for further development and integration of the wide array of systems onboard the vessel. The first tests comprised riserless drilling operations and a series of hydraulic piston coring (HPC) operations designed to evaluate the basic operational capabilities of the system.

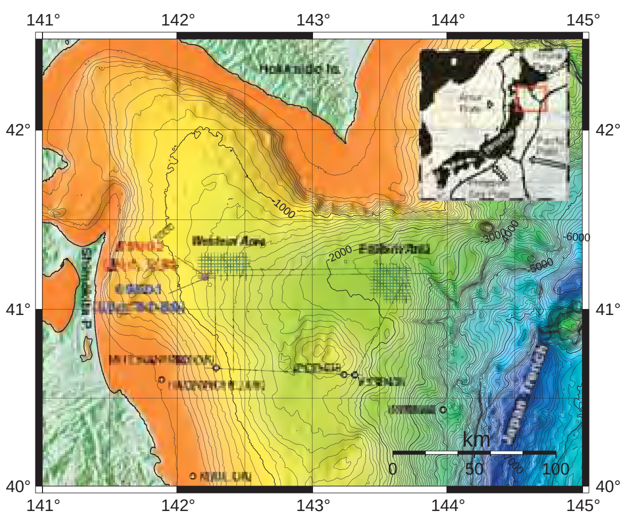

Figure 1. Location of non-riser and riser shakedown operations in the Shimokita area, offshore Tohoku, Honshu, Japan (red and blue circles). Green lines indicate locations of site survey and hazard survey seismic acquisition lines. White circles indicate the locations of previous drilling operations in the area: MITI hydrocarbon exploration wells (Kuji-Oki, Sanriku-Oki, and Hachinohe-Oki) and IPOD (or DSDP) sites 438, 439 and 584 (also referred to as DSDP sites 56, 57, and 87). Inset map indicates regional location and tectonic setting.

First Shimokita Shakedown: Riserless Drilling Tests

System integration and operational testing and training procedures conducted offshore of northern Honshu in October 2005 focused on pipe handling, drill-string construction, ship positioning, riserless drilling, and hydraulic piston coring. Additional operations focused on core handling, curation, description, and measurement using the onboard laboratory facilities.

Drilling tests included the full use of the pipe-handling and drill-string assembly system. Drill pipe was delivered to the fingerboard (the pipe-section deployment rack, Fig. 2) using the deck cranes, pipe racker, and pipe transfer system. The iron roughneck and the power swivel were used to position and attach successive drill-pipe sections to the drill string, and the entire assembled drill string, with drill bit and HPC assembly attached, was lowered to the seafloor. All pipe assembly and drilling operations were controlled from the drillers' house on the rig floor, and drilling was conducted via the top-drive assembly attached to the derrick. Coring operations were conducted by lowering core sleeves through the drill string to the bit and by collecting core through actuating the HPC system. Cores were retrieved with the coreline winch and delivered to the core receiving area. Throughout the operation, position was maintained and monitored from the drillers' control area and the bridge using the dynamic position system to control the vessel's six 360° azimuth thrusters and one fixed bow thruster. Approximately 120 m of core was retrieved from two sites during this testing operation.

Laboratory operations began with receiving, labeling, measuring, and marking of cores, entry of core data into the J-CORES database, headspace gas monitoring for safety, sampling for microbiological research, and cutting of cores into sections. Core sections were transported to the core laboratory for x-ray computer tomography scanning, whole-core multi-sensor core logging (MSCL), QA/QC analysis for pore fluids and gas, and further microbiological sampling. Core sections were then split lengthwise into working and archive halves. Archive halves were subjected to non-destructive measurements and analyses, including smear-slide studies for sedimentological and micropaleontological analysis, color spectrum and image scanning, split-core MSCL, and x-ray fluorescence scanning. Working halves were used for visual core description, and sub-samples were collected for analysis of density, porosity, velocity, sedimentology, paleontology, paleomagnetism, and petrography. Paleomagnetic analyses of whole cores were conducted in the laboratory's shielded magnetic-field-free room in February 2006. All data collected via this array of laboratory procedures were entered and stored in the onboard J-CORES database, which was used for display and presentation of data and initial interpretations.

Upcoming Tests, New Equipment, and Upgraded Capabilities

From August to October 2006, a full riser drilling operational test will take place in the same area as the initial riserless drilling shakedown operations, in water depths of 1000 m (Fig. 1). These tests will incorporate every aspect of riser and riserless drilling, coring, logging, casing, and hole completion. Riserless drilling will be used to establish pilot holes and the initial borehole required for installing the casing, wellhead, and BOP (Fig. 2). The newly installed, remotely operated vehicle (ROV) will be used to help install, observe, and manipulate the seafloor assemblies, as well as monitor safety and operational parameters during drilling. Riser pipe will be run from the ship to the BOP on the seafloor, and riser drilling with HPC and rotary coring facilitated by drilling mud circulation will take place to a planned depth of over 2200 m below the sea-floor. These operations will be conducted in concert with full-scale laboratory operations and the initial testing of mud, cuttings, and mud-gas logging capabilities.

Figure 2. External view of *Chikyu*'s blow out preventer (BOP). BOP hangs from riser pipe attached to high-powered winches on ship's derrick and will be deployed onto seafloor through moonpool below drilling platform. Note person on left for scale.

Following completion of the drilling and laboratory tests off Shimokita Peninsula in the fall of 2006, D/V *Chikyu* will embark on an approximately 6–7 month period of riser drilling organized by JAMSTEC/CDEX through a collaborative effort with industry. The borehole data from these operations, likely to take place as far away as the western Indian Ocean, will be proprietary to the industry group that finances them; however, the operational experience gained from the drilling activities will be shared with onboard CDEX personnel and will help in further testing and development of the riser-drilling capability of the platform.

Figure 3. High powered top drive and pipe handling system, setting a 4-stand drilling pipe to the pipe racker.

All of these preparations and tests are focused on readying the entire operation for the start of IODP operations in September 2007, when the D/V *Chikyu* is scheduled to begin drilling operations in the Kumano Basin area of the Nankai Trough, all as an integral component of the NanTroSEIZE project (Tobin and Kinoshita, 2006).

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Figure Credits

Photos courtesy of Japan Agency of Marine-Earth Science and Technology (JAMSTEC)

Related Web Link

http://www.jamstec.go.jp/chikyu/jp/index.html

Investigating Maar Formation and the Climate History of Southern Argentina–the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO)

by Bernd Zolitschka, Hugo Corbella, Nora Maidana, and Christian Ohlendorf

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Evidence is increasing that the Southern Ocean plays a key role in the global climate system. The southern hemisphere contains more than 90% of the world's ice, and eighty-one percent of its total surface area is covered by oceans. On global terms, the most extreme oceanic character is encountered between 40°S and 60°S latitude, where land (Patagonia and a few islands) comprises only 2% of the surface area. Terrestrial archives of past climate changes are thus extremely scarce at these latitudes. As Patagonia is subject to shifts in polar and mid-latitude winds, pressure fields, and precipitation regimes, as well as to variations related to the El Niño Southern Oscillation (ENSO) and the Antarctic Oscillation (AO), it has the unique potential to record variations in the hydrological cycle, changes in aeolian dust deposition, the frequency of volcanic activity, and other natural forces that control climatic conditions. Lake sediments can provide important archives for such terrestrial climatic and environmental reconstructions. In the semi-arid steppe region of Patagonia, however, most of the lakes are periodically dry or ephemeral. One exception is the 100-m-deep crater lake Laguna Potrok Aike (Fig. 1), a 770 ± 220 thousand year old maar situated in the province of Santa Cruz, Argentina. The lake is located in the Pali Aike Volcanic Field (Fig. 2), the southernmost back-arc Neozoic volcanic field of South America. As Laguna Potrok Aike has not been reached by any Pleistocene ice advance during the last 1 Ma, it is potentially the only mid-latitude lake in the Southern Hemisphere with a continuous sedimentary record covering several glacial to interglacial cycles. In addition to global reconstructions, regional climatic variations represent other important aspects of research.

Seismic surveys and multidisciplinary reconstructions based on 1-m gravity and 19-m piston cores at Laguna Potrok Aike form the basis for the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO) to be developed within the framework of the International Continental Scientific Drilling Program (ICDP). Data from four seismic surveys demonstrate that the lake sediments exceed 150 m in thickness and overlie several hundred meters of volcanic breccias. These data clearly make Laguna Potrok Aike a well-suited site for terrestrial climate reconstructions of the Southern Hemisphere. In addition, they enable investigations about the formation of phreatomagmatic craters which have never been studied before by coring into a relatively young, mid-Pleistocene maar structure.

The recent PASADO workshop (Rio Gallegos, Argentina, 15–19 March 2006) discussed the scientific goals and implementation plan for drilling deep into the lakebed with the Global Lake Drilling Facility (GLAD 800) system. Fifty-two participants from five continents, eleven countries, and a wide spectrum of disciplines participated in the meeting. The scientific program started with a series of twenty-one talks on the regional background and limnogeological results from Laguna Potrok Aike. The workshop included a field trip to the Instituto Nacional de Tecnologia Agropecuaria (INTA) field station at Potrok Aike (Fig. 1) to introduce the potential drilling sites. The participants formed three groups focusing on (a) technical and logistical issues related to the GLAD 800 deep drilling, (b) volcanic evidence, and (c) records of environmental change.

The workshop continued with twenty-five additional talks subdivided into eight topical sessions. The first session focused on the ICDP with regard to funding and support, technical aspects of using the GLAD 800 system, and first-hand experiences of the Petén-Itzá Drilling Project (see report in this issue on page 25). The operations of this ICDP lake-drilling project were accomplished only a few days

Figure 1. Overview of Laguna Potrok Aike from prominent basalt escarpment. This 770 ± 220 ka old maar lake is located at approximately 52°S, 70°W in Santa Cruz province, southern Patagonia (Argentina). Lake elevation = 113 m, depth = 100 m, and diameter = 3.5 km.

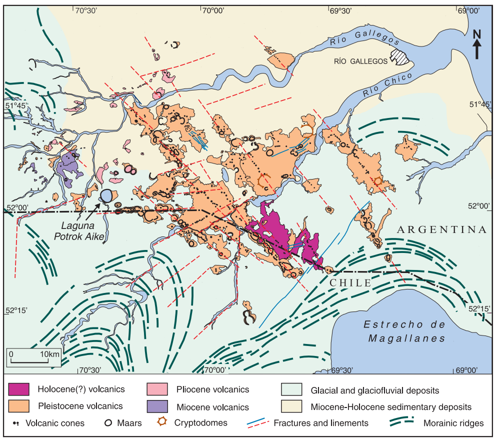

Figure 2. Volcanic map of Pali Aike Volcanic Field in southern Patagonia (Argentina), showing radiometric ages of Pliocene to late Quaternary volcanic back arc (modified after Corbella, 2002).

before the PASADO workshop started. The next session on understanding the evolution of maar volcanoes emphasized the importance of drilling into young maar structures for a better understanding of phreatomagmatic eruptions of such craters, and a subsequent session on the history of volcanic eruptions and tephrochronology established the study of volcanic ash layers as an important tool for inter-site and inter-archive correlation as well as for improving the time control of sedimentary records. The fourth session on deciphering high-frequency environmental variations introduced methods for downhole logging and non-destructive analysis of sediment cores that potentially provide ultra-high resolution data of environmental variations, whereas the fifth session on reconstruction of the Earth's magnetic field and rock magnetics demonstrated the possibilities of establishing a paleosecular variation record that might serve as another tool for stratigraphic correlation and of rock magnetics as a means to develop a magnetic proxy for climate change. The largest session on reconstruction of lacustrine and catchment-related environmental conditions focused on pollen, diatoms, chironomids, non-siliceous algae, and charcoal as paleobiological indicators for quantitative climate and environmental reconstruction. A subsequent session on tracing atmospheric dust and volcanic aerosols considered monitoring approaches and isotopic analyses of aerosols, and the final session on human impact and modeling focused on archaeological issues related to the Pali Aike Volcanic Field and to modeling of sedimentation processes within the lake.

On the last day, the participants discussed, in the context of testable hypotheses the technical aspects of scientific drilling, including potential drilling sites, appropriate target depths, and the volcanological, inorganic, and organic aspects of core analysis.

Altogether, the PASADO workshop addressed several issues related to Earth history and climate, natural hazards, and volcanic systems during past glacial to interglacial cycles. Specific topics included quantitative climatic and environmental reconstruction, paleosecular variation of the Earth's magnetic field, fire history, frequency of volcanic activity and tephra fallout, dust deposition, evolution of phreatomagmatic maar craters, and the history of regional vol-canic activity. It was concluded that dust and tephra records might provide important links between this terrestrial record and marine sediment archives and ice cores from Antarctica, enabling the resulting reconstruction of climate variability to be compared statistically with global circulation model (GCM) simulations of this region.

The scientific program with a list of participants, the abstracts of scientific presentations, and the excursion guide have been published as special issue of Terra Nostra (Zolitschka, 2006). Further information about PASADO and how to join this international effort can be obtained from http://www.salsa.uni-bremen.de.

Acknowledgements

The PASADO workshop was organized by the team of GEOPOLAR (Institute of Geography, University of Bremen, Germany) and hosted by the Universidad Nacional de la Patagonia Austral (Río Gallegos, Argentina). This workshop was supported logistically by the Government of Santa Cruz and by the INTA, while the major financial support came from the International Continental Scientific Drilling Program (ICDP).

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Related Web Link

http://www.salsa.uni-bremen.de

HOTSPOT: The Snake River Scientific Drilling Project—Tracking the Yellowstone Hotspot Through Space and Time

by John W. Shervais, Michael J. Branney, Dennis J. Geist, Barry B. Hanan, Scott Hughes, Alexsander A. Prokopenko, and Douglas F. Williams

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Mantle plumes play a crucial role in Earth's thermal and tectonic evolution. Plumes have long been implicated in the breakup and rifting of continents, and plume-derived melts play a significant role in the creation and modification of the sub-continental mantle lithosphere. Hotspot volcanism in the oceanic lithosphere has been the subject of intense recent study by the Hawaii Scientific Drilling Project, and studies conducted by the Integrated Ocean Drilling Program (IODP) will examine further the role of mantle plumes in oceanic settings. These drilling efforts provide baseline information about where mantle plumes originate, how they behave, and what the volcanic products of these processes are. In contrast, the impacts of hotspot volcanism on the continental lithosphere are poorly understood because active continental hotspot systems are limited to surface exposures of volcanic provinces that are too young to be exposed by erosion.

The Snake River Plain volcanic province, which begins under eastern Oregon, U.S.A. and ends at the Yellowstone plateau about 350 km to the east, represents a hotspot track beneath the continental crust (Fig. 1). Basalts of the Snake River Plain are compositionally similar to ocean-island basalts and preserve a record of volcanic activity that spans over 12 Ma. The Snake River province is still active today, with flows as young as 6000 years, and it represents a world-class example of active, intra-continental, mantle-plume volcanism. In addition, the western Snake River Plain preserves an archive of late Neogene paleoclimatic evolution hosted within deep-water lacustrine sediments. The complete record of volcanic activity can only be sampled by drilling because the plain is young and tectonically undisturbed, with limited exposure of the stratigraphic sequence.

Figure 1. Digital elevation model of southern Idaho showing Snake River Plain and its relation to flood basalts of Columbia Plateau in Washington and Oregon (CP), Basin & Range area (B&R), and Yellowstone plateau (YP). Potential drilling sites are shown as red stars.

The project "HOTSPOT: Scientific Drilling of the Snake River Plain" held its inaugural workshop in Twin Falls, Idaho, U.S.A. on 18–21 May 2006. This inter-disciplinary workshop, sponsored by the International Continental Scientific Drilling Program (ICDP), explored the major scientific and logistical issues central to a transect of boreholes along the hotspot track and addressing the geochemical evolution of continental lithosphere in response to interaction with deep-seated mantle hotspots or plumes. A series of four to six bore holes is envisioned, each about 1.5–2.0 km deep and located along the axis of the Snake River Plain. The holes will specifically target the origin and evolution of hotspot-related volcanism in space and time. To accomplish scientific and logistical planning, sixty scientists from six countries attended the workshop.

During the first day, keynote speakers highlighted different aspects of the hotspot system, including heat flow, tectonics, basalt and rhyolite geochemistry, and paleoclimatic and cyclostratigraphic studies of paleolake sediments deposited in basins formed in the wake of the hotspot. Results of the Hawaii Scientific Drilling Project and the logistics of basalt drilling were described as well. The first day closed with presentations on drilling platforms, downhole logging tools, cyberinfrastructure, and the proposal process in the ICDP and Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC). The second day consisted of a field trip to potential drilling sites that contrasted stratigraphic differences between the basalt-dominated eastern Snake River Plain and the sediment-rich western plain that is overlain and underlain by hotspot basalts with distinct origins. On the third day, break-out sessions were conducted on the following topics, ending with ideas on how to target a drilling campaign addressing key questions in each of these areas: basalt geochemistry and isotope chemistry, rhyolite geochemistry and volcanology, hydrothermal systems and alteration, sedimentation-paleoclimate-cyclostratigraphy, and geophysics. The day concluded with a visit to the Snake River Canyon north of Twin Falls to examine a high-temperature rhyolite flow, overlain by fluvial and lacustrine sediments, and several hundred feet of basalt lava flows. The final day saw a wrap-up session that summarized findings of the preceding sessions and a layout of an action plan to move the project further towards realization.

A key goal of the Snake River Plain Scientific Drilling Project is to constrain how mantle hotspots interact with the continental lithosphere and how this interaction is reflected in the geochemical evolution of the mantle-derived magmas. To achieve these goals, a transect is proposed over the paleo-continental margin across different zones of the lithosphere. During the first stage, lavas that erupted through Mesozoic accreted terranes of oceanic provenance should be drilled. Later drilling will sample lavas derived from magma that traveled through a progressively thicker and older lithosphere of Proterozoic to Archean age and will illuminate how changes in the thickness, age, and composition of the underlying mantle lithosphere affect basalt chemistry. This strategy will also allow the sampling of extensive sections of basalt at relatively low cost. In addition, the unique potential to resolve unanswered questions about the evolution of the Plio-Pleistocene paleoclimate by drilling paleo-Lake Idaho was discussed.

It was also suggested that one deep hole should attempt to penetrate the early high-temperature rhyolites underlying the basalts, to constrain both the volume of felsic eruptives and the crustal response to passage of the hotspot. Since most Snake River Plain rhyolites represent crustal melts formed in response to the intrusion of mafic magma into the lower and middle crust, the volume of rhyolite allows one to infer the volume of mafic magma trapped in the crust. The nature of pre-rhyolite volcanism and sedimentation reflects the crustal response to the passage of the hotspot. It was agreed that the best strategy to achieve this goal is to deepen one of the existing bore holes already penetrating rhyolite at depth at the Idaho National Laboratory (INL) site.

The western Snake River Plain graben contained a deep lake (Lake Idaho) for much of its late Pliocene to early Pleistocene history. Lake Idaho sediments include diatom-rich rhythmites spanning the Pliocene-Pleistocene boundary and preserve a detailed record of climatic change during this critical transition. Scientific objectives include (1) the late Neogene history of North Pacific atmospheric water transport into the Great Basin of the western North American craton and possible linkages to the initiation of Northern Hemisphere glaciation, (2) the response of the Great Basin hydrological system to the Pliocene climatic optimum, and (3) the development of a master reference section for later examination of lacustrine sediments interbedded with basalt and rhyolite in the eastern Snake River Plain. Proponents of the Lake Idaho Drilling component will develop the rationale for this scientific effort independently, but complementary with the planned drilling of the volcanic rocks that underlie the lake sediments.

The HOTSPOT workshop benefited from bringing together scientists from a wide range of disciplines to address issues related to the central theme of hotspot volcanism. In particular, combining studies of hotspot dynamics and paleoclimate records within the sedimentary systems forming in response to hotspot passage provides a strong opportunity for interdisciplinary science. The geochemical studies will complement EarthScope investigations of crustal and lithospheric structure by providing mass-balance constraints on melt extraction from the mantle and partial melting of the crust. A significant educational and outreach component is planned as well.

The participants resolved to pursue this project by submitting pre-proposals to the ICDP and the U.S. National Science Foundation (NSF). This planning effort will require compiling a database of existing geological and geophysical data and full coordination with EarthScope geophysical investigations A HOTSPOT session at the American Geophysical Union meeting in San Francisco in December 2006 is in preparation.

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Related Web Links

http://snakeriver.icdp-online.org
http://www.earthscope.org/

Workshop on the Development of the CoreWall Suite of Applications

by the CoreWall Steering Committee

doi:10.2204/iodp.sd.3.15.2006

Workshop Goals

The CoreWall project was funded recently (March 2006) by the U.S. National Science Foundation (NSF,). It is charged to develop a basic suite of data integration and visualization applications for broad use in the ocean-, lake-, continental-, and ice-coring communities. A CoreWall workshop was held on 8–10 May 2006 in Washington, D.C. to explore possible development pathways for the CoreWall Suite of applications. The original CoreWall application was envisioned by the lake-core community who needed a better way to visualize their cores, do visual core descriptions, and share core photos and data in an integrated environment. A collaboration of earth and computer scientists from four universities and one consulting firm was established to accomplish these goals.

To define the appropriate specifications and requirements of the coring communities, the workshop brought together forty-two participants from a variety of ocean and lake drilling groups, such as the Integrated Ocean Drilling Program (IODP), the International Continental Scientific Drilling Program (ICDP), ANDRILL, and LacCore, as well as databases like PetDB, SedDB, and PaleoStrat, application developers from GeoMapApp and Match, web portals such as CHRONOS, educators such as the Science Museum of Minnesota (U.S.A.), and other interested scientists.

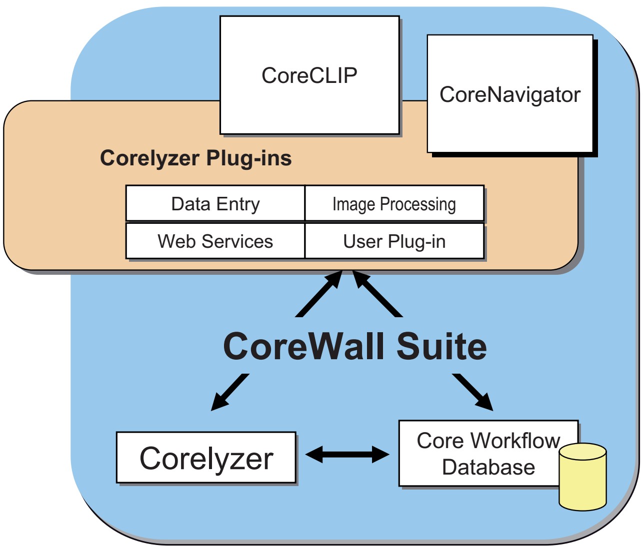

Figure 1. Components of CoreWall Suite.

The first goal of the workshop was to introduce the participants to the current stage of CoreWall development. While the name implies something physical and perhaps large, it is actually a group of open-source, cross-platform software applications that have modest hardware requirements and can be used on anything from a laptop to a multi-panel display depending on project needs.

The CoreWall Suite currently consists of four parts, each having a different purpose for viewing, integrating, or exploring data (Fig. 1):

1) The Corelyzer is the primary visual integration workspace that allows users to view depth-registered data and images from any compatible database. At the workshop, the data and images from Ocean Drilling Program (ODP) Leg 199 and from ICDP/NSF Lake Titicaca drilling project were used as examples of how the Corelyzer can scale from medium- to large-scale projects and handle large datasets. Corelyzer is easily expandable through the development of custom plug-ins. It can also pull data from the Web, as demonstrated at the workshop with a newly developed CHRONOS Web Data Portal plug-in.

2) The Workflow Database is a locally working database that allows for data access, Web services, and other databases, as well as synchronization between multiple CoreWall setups or databases, and it is intended for use in remote collaborations where data and images are being shared.

3) The Core-Log-Integration-Platform (CoreCLIP) application revises the SPLICER (stratigraphic composite builder) and SAGAN (core-log mapping) software that was previously a UNIX application used mainly by the ODP. CoreCLIP will provide a stand-alone application and a Corelyzer-ready plug-in with many new features such as the ability to use images to assist stratigraphic composite building, an integrated text parser to improve data entry, contextual help and tutorials, and options to add new depth-correlation algorithms to improve composites and depth mapping results.

4) The CoreNavigator is a data discovery tool that has the ability to browse data in a 2- or 3-D geographic context. It uses VRML (Virtual Reality Modeling Language), to provide a visual means of comprehending cored stratigraphic datasets, integrated with seismic and oceanographic data when available. CoreNavigator displays are computed directly off databases.

Prior to the current project funding, the Corelyzer software already had been under test-bed or prototype development for two years, and the developers had established a number of informal collaborations with several groups, including the Joint Oceanographic Institutions (JOI), the LacCore facility at the University of Minnesota, CHRONOS, and ANDRILL. The LacCore Facility has provided an important testing ground that drove the initial requirements and desired features of the software by getting the community to explore possible uses.

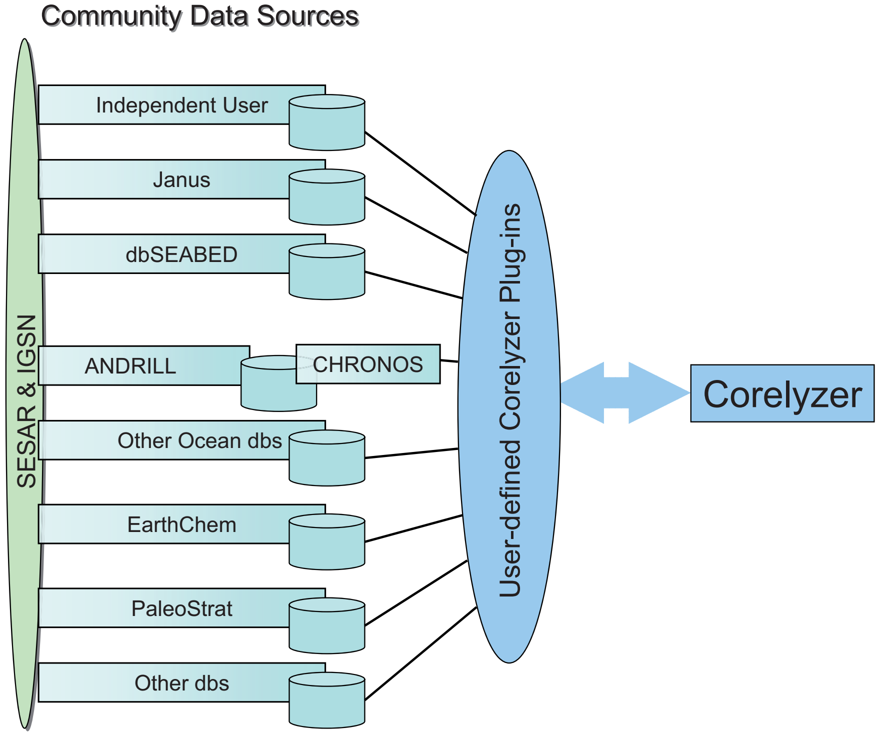

Figure 2. Projected interfaces between user community data bases and CoreWall suite. System for earth sample registration (SESAR) and international geosample number (IGSN) are sample registration systems, assigning unique id's to physical geological samples.

The two existing Corelyzer plug-ins were developed as a result of our ongoing collaboration with ANDRILL and CHRONOS. The first one is a connection between PSICAT, a sedimentary visual core description tool written for ANDRILL by CHRONOS, and the second plug-in is designed to connect Corelyzer to JANUS, the ODP database through the CHRONOS portal. Images and physical property data from multi-sensor core logger (MSCL) track systems can all be pulled on demand via a seamless Web service. This development will be tested in the 2006–2007 Antarctic field season of ANDRILL when we deploy Corelyzer at Crary Laboratory, McMurdo Station.

A separate collaboration with the Borehole Research Group of Lamont-Doherty Earth Observatory at Columbia University was initially an ODP legacy project to update the SPLICER and SAGAN stratigraphic software by making it a more portable, cross platform package for use on all IODP platforms and other coring communities. As part of the CoreWall project, the CoreCLIP software (Core-Log-Integration Platform) will be further enhanced. One possible enhancement presented at the workshop includes adding a dynamic, core-data mapping package, similar to the capabilities of the Match software, developed at Brown University (Lisiecki and Lisiecki, 2002).

One concern expressed at the meeting was the risk of CoreWall trying to do too many things for too many different groups this early in the development process. The foundation of the CoreWall Suite is its ability to integrate core images with all other data associated with the core and to display them in a scalable manner. It became immediately clear at the workshop that individual user communities would like to integrate new functionality and features into the CoreWall Suite. To address this desire, our team has created a plug-in structure that allows programmers to extend the functiona lity of the base software. For example, open-source tools such as the National Institutes of Health's (NIH) image processing and analysis tool IMAGE-J could be made accessible through a plug-in. A capability to add depth-registered annotations to aid visual core description and a possible means for Internet collaborations were also popular items on the wish list. Core repositories such as the LacCore Facility in Minnesota were also looking at it as a means for tracking the sampling of cores, and educators and museum exhibit designers had many ideas for displaying primary scientific data with attached multi-media for classrooms and exhibits.

The most exciting part of the workshop was the convergence on the need for better data visualization by almost all communities represented. The timing of the CoreWall Project is driven in part and will be enhanced by co-developments of new global databases, global sample registration initiatives, data web portal developments like SEDIS (IODP), CHRONOS, dbSEABED, EarthChem, and others. CoreWall is envisioned to work with the larger community on a variety of levels and to empower all users to find, access, display, and use available data (Fig. 2). The goal is to allow users to do their own science, interact seamlessly with multiple remote databases to integrate new data, and even create unique sample IDs through IGSN for new samples and analyses.

The discussion of possible CoreWall uses in educational and museum settings produced many interesting ideas. Two of them were chosen as immediate targets. The first one was to create a set of "Core Best Hits" to be compiled within CoreWall complete with available MSCL data, smear slides, thin-sections, and comments. Example curricula co-developed by JOI, ANDRILL, or LacCore will be included in packaged downloads. Instructors can then use these examples to talk about climate change, plate tectonics, or the K-T extinction. Another potential application was the use of CoreWall in an informal educational or museum setting. In such settings, the computer hardware will be configured with vertical screens to show the data in their proper orientation using a simplified trackball interface (Fig. 3). This configuration will be used in Water Planet, an NSF-funded, 550-m^2 traveling exhibit being developed by the Science Museum of Minnesota.

There was a general agreement among the workshop participants that the main functionality of the CoreWall Suite is well-suited to serve the visual integration needs of various communities that study cores. The visual integration capability alone would be a huge step forward for all of these communities if it can be accomplished in a robust, simple, and intuitive way.

The CoreWall Website (http://www.corewall.org) offers further information, a download link to the current version (0.68) of the Corelyzer software, and a Corelyzer Tutorial page. It also offers updates and news about the software and the project and presentations made at the workshop. A public CoreWall wiki page is available at http://sqlcore.geo.umn.edu/CoreVault/cwWiki/index.php/Main_Page for those interested in contributing comments or suggestions on the project development. A detailed CoreWall workshop report is forthcoming.

Acknowledgements

The CoreWall Consortium appreciates the generous funding of the JOI USAC to host this workshop and to have made available their Washington, D.C. offices for the meeting. Special thanks to Holly Given (JOI, Director USSSP), Robert Burger (JOI Associate Program Director, USSSP), Frank Rack (JOI, Director of Ocean Drilling Programs), Julie Farver, and Rob Wright for planning and technical support.

Figure 3. CoreWall setup for visual core description in laboratory.

Table 1. Developers of CoreWall Suite

Electronic Visualization Lab, University of Illinois at Chicago
Emi Ito, LacCore, University of Minnesota, Project coordinator
Paul Morin, LacCore, National Center for Earth-Surface Dynamics, University of Minnesota, Interface between programmers and users
Sean Higgins, L-DEO-Borehole Research Group at Columbia University, Oversees CoreCLIP development, interface to IODP
Arun Rao, Julian Chen, Jason Leigh, Andy Johnson, and Luc Renambot, Programmers and advisors for Corelyzer
Bill Kamp, IAGP Partners Limited, Inc., Programmer for CoreCLIP and Core Workflow Database
Chris Jenkins, INSTAAR, University of Colorado, Programmer for CoreNavigator

Reference

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Related Web Links

http://www.corewall.org
http://www.evl.uic.edu/cavern/corewall/publications.php#workshop
http://sqlcore.geo.umn.edu/CoreVault/cwWiki/index.php/Main_Page
http://www.laccore.org
http://www.chronos.org
http://portal.chronos.org/gridsphere/gridsphere?cid=tools_psicat
http://www.andrill.org

Workshop on the Campi Flegrei Caldera Deep Drilling Project

3–15 November 2006, Naples, Italy
Application deadline: 22 September 2006

Campi Flegrei caldera, located just west of Naples (Italy), represents an ideal natural laboratory for understanding the most explosive volcanism on Earth and its impact on a densely populated area. The location of Campi Flegrei, half onland and half offshore, presents a unique opportunity for a joint IODP and ICDP scientific project.

The international workshop is co-sponsored by the ICDP and ESF-ECORD to assess precisely the main scientific goals and the best procedures to achieve them by deep drilling. The main targets are:

1) Reconstruction of the deep caldera structure, thermal state, stress and rehology (location of shallow magma reservoirs and brittle-ductile transition)

2) Reconstruction of the geothermal system and its interaction with magma reservoirs during eruptive and pre-eruptive phases

3) Determination of best strategies for geothermal energy exploitation

4) Improvement of shallow and deep monitoring technologies and risk mitigation

Limited funding is available for travel and participation. Members of the international scientific community who wish to contribute or participate in the Workshop are invited to submit an application with their name, institution, contact details, research interests and expertise.

Contact: Giuseppe De Natale (denatale@ov.ingv.it) and Claudia Troise (troise@ov.ingv.it)

COREF Workshop

15–19 January 2007, Okinawa-jima, Japan

Application deadline: 30 November 2006

The COREF (coral-reef front) Project proposes a continental scientific drilling campaign in the Ryukyu Islands (northwestern Pacific Ocean) to investigate the dynamic response of the coral-reef fronts in this region to Late Quaternary climate and sea level change. The project shall answer the following questions: 1) what is the nature and magnitude of coral-reef front migration in the Ryukyus? 2) what is the ecological response of coral reefs in the Ryukyus to late-Quaternary climate change? 3) what is the role of coral reefs in the global carbon cycle?

The proponents of the COREF Project announce an international workshop to be held under the auspices of the ICDP. We invite scientists from all countries who are interested in coral-reef responses to climatic changes on various time scales. Limited travel funds are available to help offset the costs associated with workshop participation.

More information and registration at http://www.dges.tohoku.ac.jp/igps/iryu/COREF/

ICDP Workshop on Drilling the North Anatolian Fault (Turkey)

April 2007, Istanbul, Turkey

A deep borehole observatory in the North Anatolian Fault Zone (NAFZ) will allow studying earthquake activity close to the seismically active part of the fault zone at a depth of 4–15 km. A borehole array will enhance the resolution of seismological observations by several orders of magnitude. This would allow the study of rupture processes, heat and fluid flow, orientation and magnitude of local stresses and strains at the fault, the *in situ* strength of a major plate boundary fault. Seismicity and temporal changes of physical properties could be monitored for several decades and prior to an expected large earthquake. This would give new insight into potential transients and scale dependence of physical processes operating in a fault zone during the seismic cycle.

A workshop on 'Drilling the North Anatolian Fault' will be held in April 2007 in Istanbul, Turkey to discuss and strengthen plans for a deep drilling project combined with the installation of a deep borehole observatory at the North Anatolian Fault Zone. Colleagues from the international science community and drilling specialists that are involved in current ICDP fault drilling projects are invited to join. During the workshop a science and drilling plan for a deep drill hole will be generated, and a draft for a full drilling proposal to be submitted to ICDP in Fall 2007 will be prepared.

Contact: Georg Dreesen (dre@gfz-potsdam.de)

Townhall Meetings, Fall AGU

Several drilling-related town hall meetings are taking place during the Fall AGU 2006 in San Francisco. Dates and locations were not set as of the publication date of this journal.

For the IODP town hall meeting please visit **http://www.iodp.org** to find the most recent information about the meeting.

The ICDP/DOSECC town hall meetings will take place on Monday, 11 December, 19:30–20:30 at the Mariott Hotel. Time and date await confirmation, so visit **http://www.icdp-online.org** for the latest information.

For the SHALDRIL town hall meeting please visit **http://shaldril.rice.edu**.

SHALDRIL: Quick Drilling on the Antarctic Continental Shelf

SHALDRIL (SHALlow DRILling on the Antarctic Continental Margin) was designed to drill through stiff glacial overburden too hard for piston coring, to sample older deposits of the Antarctic continental shelf appearing close to the seafloor. SHALDRIL operates between the continental slope, where traditional drill ships work, and the fast-ice zone, where projects like ANDRILL operate. The SHALDRIL project uses a mobile drilling platform capable of operating in ice-covered waters, and a drilling system that can retrieve core within a few hours.

SHALDRIL II took place from 1 March to 5 April 2006 in the northwestern Weddell Sea. The primary drilling targets were in the northern portion of the James Ross Basin, known to contain one of the thickest, most complete Neogene successions on Antarctica and its adjacent margins. Seismic investigations had revealed a virtually continuous sequence of seaward-dipping strata on the continental shelf. The sequence spans the late Eocene through Pleistocene, based on correlations to outcropping strata on Seymour Island and confirmed by results from this cruise.

SHALDRIL I (March to April 2005) faced ice reaching nearly 10/10 coverage. The ice in 2005 was typically thin, young ice thet did not affect the ability to hold station. SHALDRIL II encountered large floes of very thick, multi-years sea ice (Fig. 1), that had to be treated like icebergs as the research vessel-icebreaker *Nathaniel B. Palmer*, would not be able to hold station. In addition the ice drift was frequently changing course and at a speed of almost 1 knot. The longest time achieved on station was eighteen hours, making it impossible to drill through even 10 m of glacial overburden for older strata; Hence the primary target sites could not be drilled as planned. Focus was put on the alternate sites having thinner overburden. These had been selected using the available seismic and stratigraphic framework. Selection proved to be successful, as the third drilling attempt reached the targeted Late Eocene strata.

Ice around *Nathaniel B. Palmer* during drilling operations. Photo by Captain Mike Watson.

Severe ice conditions still prevented most drilling attempts even on alternate sites. The SHALDRIL team therefore decided to conduct a seismic survey to select alternate drilling sites near the Joinville Plateau, where ice conditions were better. On the margin of the plateau, strata from deep in the sedimentary section were observed to onlap acoustic basement. This provided a good target for a “drill and run” strategy. This area had not been mapped or imaged previously; however, drilling was successful and two holes recovered the targeted Pliocene material. During drilling operations on the third hole, two breaks occurred in the drill string, resulting in the loss of material. These breaks can probably be attributed to strong bottom currents in the region, leaving the expedition with only one complete bottom hole assembly remaining on board. Since it was still early in the cruise, it forced the expedition to return to the drifting ice rather than dealing with the difficult sub-sea currents. Drilling during the remainder of the expedition remained difficult, but in the end paid off by successively reaching all targeted intervals with short holes, making it possible to splice together a full stratigraphic succession for the Antarctic correlating core with seismic images.

In conclusion, SHALDRIL II proved, that a flexible, quickly operating platform can yield excellent results in the unpredictable environments of the Antarctic. This was also made possible due to the excellent work of the drilling contractor Seacore Ltd.

SHALDRIL I and II tested the ship and the drilling and coring systems under the most adverse conditions and have gathered considerable data for planning future cruises. The ship is capable of holding station in winds up to 45 knots, the drilling system is capable of penetrating up to 20 meters of glacial overburden and sampling strata below within 24 hours time. Core recovery in partially lithified sedimentary material is greater than 80%.

For more information about SHALDRIL and reports of the cruise please visit http://shaldril.rice.edu. SHALDRIL will host a Town Hall meeting at AGU in December 2006. Deatils will be announced on the Web page.

The School of Rock Expedition: Maximizing the Value of Transits and Program Outreach

Last November, the U.S. implementing organization for the IODP sponsored the School of Rock Expedition—a seagoing, hands-on discovery expedition for educators—during the IODP Expedition 312 transit from Victoria, British Columbia, Canada, to Acapulco, Mexico. This pilot program was designed to take advantage of the unused laboratory facility and berths on the vessel during the transit and to expose educators to the nature of scientific ocean drilling research, which depends on inquiry, technology, and teamwork as well as the data and discoveries resulting from nearly four decades of scientific ocean drilling.

Thirteen educators from the United States spent eleven days on the JOIDES Resolution learning about ocean drilling science and developing education materials, followed by two days of education and assessment work on shore. At sea, two professors with extensive scientific ocean drilling experience (Dr. Mark Leckie and Dr. Kristen St. John) provided daily science lectures and led laboratory exercises on topics related to scientific ocean drilling using ocean drilling cores and data. Supplemental lectures were provided by USIO scientists during port call (Dr. Jeff Fox) and on the vessel via videoconference from USIO/TAMU (Dr. Adam Klaus). The educators were also introduced to the procedures and equipment used by the ship's staff in the course of a two-month science expedition. After the seagoing technical staff introduced the analytical systems used in the laboratories, the educators worked with previously recovered cores and published data from fifty-six drilling sites from twenty-six scientific ocean drilling cruises to investigate scientific procedures used by shipboard scientists. The educators discovered for themselves that published scientific data are accessible and applicable to the Earth system science curricula they teach in the classroom and present in museum displays.

After inquiry-based experiences using real data were completed, the educators used their expertise to transform the content into materials appropriate for the ages and audiences they teach (grades 5–12). The outcome was the development of fifteen classroom activities based on scientific ocean drilling cores, scientific procedures, and data. In addition, twenty biographies were created to highlight the diverse career profiles of the shipboard staff, as well as three instructional lab demonstration videos. These materials were field tested in classrooms during the school year, and the participants will be attending a post-expedition meeting in August 2006 to complete the peer-review process before the activities are published. To view these activities, and the undergraduate-level educational materials developed by the scientists for the School of Rock Expedition participants, go to the "Classroom Activities" section of the JOI Learning Web page (http://www.joilearning.org).

J-DESC holds domestic IODP symposium

On 19 May 2006, Japan Drilling Earth Science Consortium (J-DESC), Ocean Research Institute (ORI, University of Tokyo), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) held the first domestic symposium on the status of the past IODP expeditions at ORI auditorium.

The symposium was aimed mainly at discussing the Japanese contribution to the past IODP expeditions and at sharing information on scientific highlights, expedition related topics (e.g., planning, staffing, life on board, etc.), and the upcoming expeditions. There were sixty-six attendees in the symposium.

IODP-MI vice-president Hans Christian Larsen illuminated the current status and future of the IODP. During the main session, Japanese co-chief scientists and participants of Expeditions 301 (Juan de Fuca Hydrogeology), 302 (Arctic Coring Expedition), and 303 (North Atlantic Climate 1) presented expedition summaries and progress reports of various projects. Finally, the upcoming NanTroSEIZE expeditions were introduced. Professor Noriyuki Suzuki, Chair of J-DESC's IODP section, concluded the symposium. J-DESC now plans to hold this domestic symposium twice a year, the next being held in November 2006.

10th Annual Continental Scientific Drilling Workshop

A workshop on continental scientific drilling was held 4–6 June 2006 at the University of California, Davis. A diverse group of forty participants heard talks from nineteen scientists on topics involving past and future continental scientific drilling projects, issues, and plans. A field trip, "Crossing a Plate Margin: Great Valley to Napa Valley," was also included in the workshop. Drilling, Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC) hosted the workshop.

Further details of the workshop and select slide show presentations are available at http://www.dosecc.org/html/workshop_2006.HTM. The 11th Annual Continental Scientific Drilling Workshop is tentatively scheduled for 3–5 June 2007.

ICDP enters second decade

The International Continental Scientific Drilling Program is launching its new phase after passing a very successful international peer review and a thorough discussion of future scientific goals in a major conference (see: Conference on Continental Scientific Drilling, *Scientific Drilling* No. 2, 2006, 43–45).

The program began in 1996 by a Memorandum of Understanding among Germany, the USA, and China. Drilling operations were funded from 1998 onward with increasing financial and operational support for several projects. The recent review served to assess the structure and past performance of the ICDP and to evaluate the new science plan. The positive review and the new science goals will form the backbone of the ICDP in the next decade.

Details on the reviews are available on the ICDP webpage at: http://www.icdp-online.org/review/.

New ICDP Web Site Online

The ICDP is proud to announce the relaunch of its Web site. Most of the previous content has already been transfered. In a few cases, some links may still guide to 'old' pages. This will be reduced step-by-step. The existing URLs for the homepage www.icdp-online.org and the individual project links remain valid.

New features include improved navigation, advanced user features, and many new options availble through the new content management system, allowing distributed editorship. We apologize for problems during the transition phase. Please visit the new ICDP web site at http://www.icdp-online.org.

Roger Larson (1943–2006): Cretaceous Magnetic Reversals, Super-plumes, and the Tectonic Reconstruction of the Pacific

by James H. Natland

From the start, Roger Larson and scientific ocean drilling ran on parallel tracks. While he was still a graduate student at the Scripps Institution of Oceanography, the Deep Sea Drilling Project (DSDP) was launched from Scripps. Close to four decades later, Roger's passing this last May at age 63 cut short an eminent career in geosciences and exploration of the ocean floor.

Roger the graduate student was mainly a practicing geo-acoustician and magnetician. His thesis parsed out for the first time the details of the opening of the Gulf of California and the magnetic character of young ocean crust. However, his attention soon turned to the mapping and calibration of the Mesozoic (M-Series) magnetic lineations in the central and western Pacific. One of the consequences of this work followed from the revelation that the M-Series anomalies and adjacent Cretaceous magnetic "quiet zone", about 37 million years of no magnetic field reversals, reveal a period of unusually high spreading rate wherever those anomalies exist (Larson and Chase, 1972). Larson and Pitman (1972) argued that the rapid emplacement of a large volume of young, warm lithosphere beneath spreading ridges displaced sea water, thus providing a cause of sea level rise and formation of epicontinental seas, extensive arc volcanism, and large-volume batholith emplacement during those non-glacial times.

Discovery of the M-Series lineations in the Pacific led Roger to be selected as one of the co-chief scientist of DSDP Leg 32 that drilled and dated Mesozoic plateaus and magnetic lineations in the northwest Pacific. Then, when subsequent integration of magnetic studies showed that the oldest part of the Pacific plate began existence as a Jurassic microplate that was surrounded by M-Series lineations spreading away

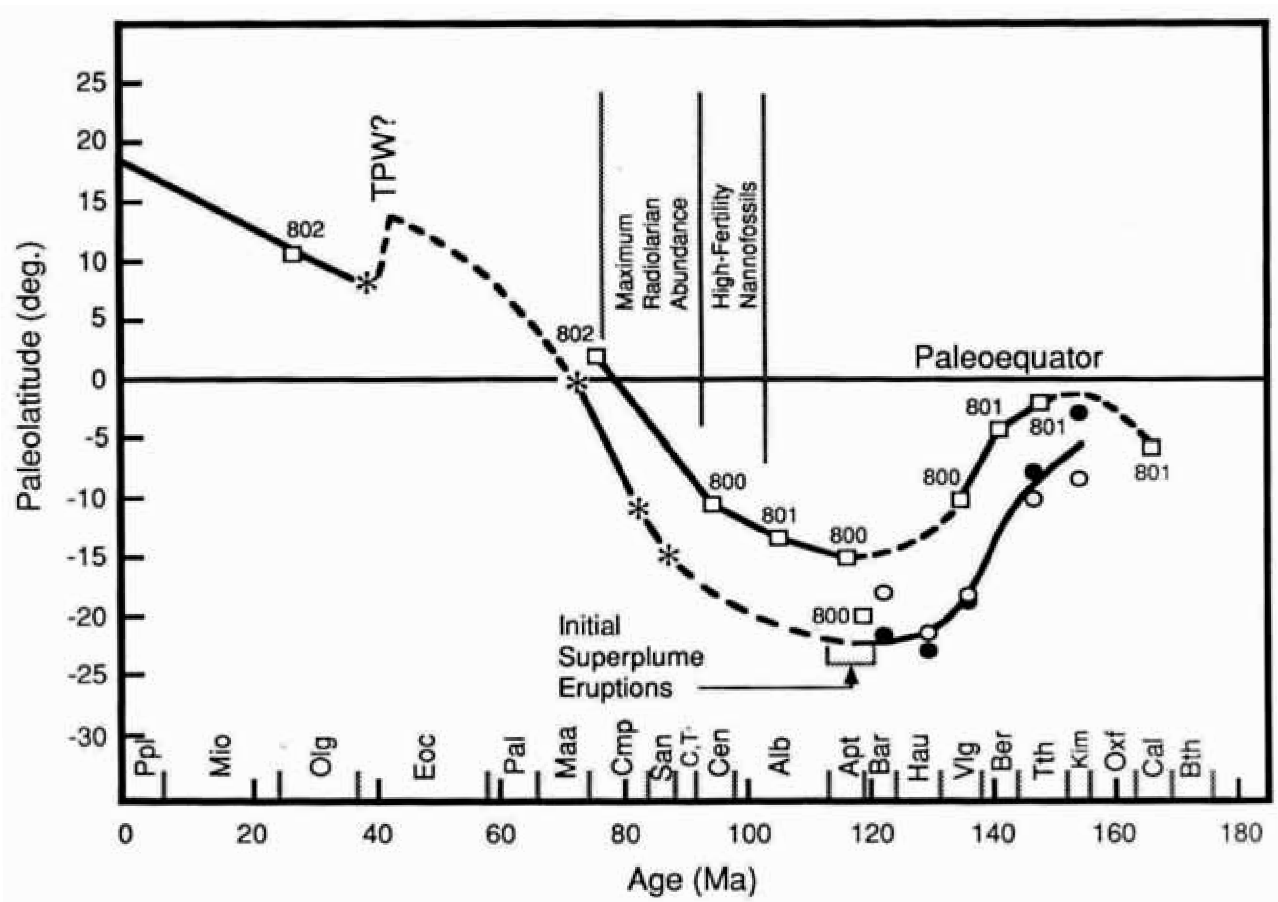


Figure 1. Possible paleolatitude history for ODP Site 801, published by Larson et al. (1992) in *Scientific Results* Volume 129 of *Proceedings of the Ocean Drilling Program.*

in all directions, Roger was selected as co-chief scientist to drill said Jurassic basement in the Nauru Basin during DSDP Leg 61. The great surprise was that the ancient basement is thickly carapaced by much younger basalt in the apparent form of a Cretaceous basin-filling outlier of the Ontong-Java Plateau. Emplacement of these lavas was evidently so rapid that it did not erase the magnetic signal of underlying Jurassic crust.

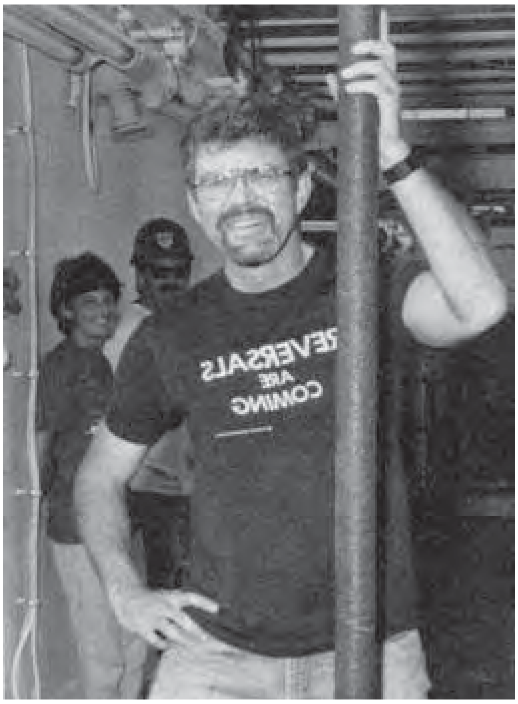
Two legacy papers published in *Geology* (1991a, 1991b) integrated the drilling results in the Pacific and set the agenda for decades of global research and scientific discussions. The first paper proposed a mid-Cretaceous mantle superplume centered on the Ontong-Java Plateau. Roger argued that only a superplume could ring the bell of the core-mantle boundary sufficiently to 'freeze' the magnetic field direction for tens of millions of years and trigger large-scale plateau volcanism and high spreading rates worldwide. The second paper explored the consequences of this cataclysmic event on sea level, global magmatism, emission of greenhouse gases, anoxic events, formation of black shales, and global warming.

During Ocean drilling Program Leg 129, with Roger as one of the co-chief scientists, Site 801 eventually reached Jurassic basalt formed at a spreading ridge. Larson et al (1992) published a splendid synthesis of the history of the Pacific Plate from the Mesozoic into modern times in the proceedings from that expedition (Fig. 1).

Roger Larson's activities extended beyond the drilling and the labs and included service in numerous community committees, including being chair of the of the Steering Committee for the first Conference on Scientific Ocean Drilling (COSOD I, 1982), chair Planning Committee of the Ocean Drilling Program (1984–1985), and chair of the U.S. Science Advisory Committee (USSAC) for the Ocean Drilling Program (1995–1997). During the initial run-up to IODP in 1996, Roger advocated Moho drilling as one of the big challenges for this new program. A decade later, IODP is sponsoring an international workshop to define a roadmap for a successful mission to Moho. In this and in many other ways, IODP will sorely miss Roger's unique ability to look over the horizon and identify global scientific problems that only this program can solve.

Acknowledgments

I thank Rob Pockalny, Jeff Fox, and Hans-Christian Larsen for their help in preparation of this article.



Roger and a 2-m long piece of Jurassic basalt recovered during ODP Leg 129 from Hole 801C in Pigafeta Basin, western Pacific. Shirt, in reverse print, says, "Reversals are coming". Photo provided by John Beck of Integrated Ocean Drilling Program.

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Schedules

IODP – Expedition Schedule http://www.iodp.org/expeditions/

	ESO Operations	Platform	Dates	Port of Origin
1	New Jersey Shallow Shelf	MSP	May–Jul. '07	TBD
	USIO Operations	**Platform**	**Dates**	**Port of Origin**
2	Equatorial Pacific Transect 1	U.S. SODV	Nov.–Dec. '07	Honolulu, U.S.A.
3	NanTroSEIZE (Stage 1) - Subduction Inputs	U.S. SODV	Jan.–Feb. '08	Honolulu, U.S.A.
3	NanTroSEIZE (Stage 1) - Kumano Basin Observatory	U.S. SODV	Mar.–Apr. '08	Yokohama, Japan
4	Bering Sea	U.S. SODV	May–Jun. '08	TBD
5	Juan de Fuca Hydrogeology	U.S. SODV	Jul.–Aug. '08	TBD
2	Equatorial Pacific Transect 2	U.S. SODV	Sep.–Oct. '08	TBD
6	Canterbury	U.S. SODV	Nov.–Dec. '08	TBD
7	Wilkes Land	U.S. SODV	Jan.–Feb. '09	TBD
	CDEX Operations	**Platform**	**Dates**	**Port of Origin**
3	NanTroSEIZE (Stage 1) - LWD Transect	*Chikyu*	Sep.–Oct. '07	
3	NanTroSEIZE (Stage 1) - Mega-Splay Riser Pilot	*Chikyu*	Nov.–Dec. '07	
3	NanTroSEIZE (Stage 1) - Thrust Faults	*Chikyu*	Jan.–Feb. '08	
	Maintenance	*Chikyu*	Mar.–May. '08	
3	NanTroSEIZE (Stage 2) - Mega-Splay Riser	*Chikyu*	Jun. '08–TBD	

SODV = Scientific Ocean Drilling Vessel TBD = to be determined
MSP = Mission Specific Platform
All dates are approximate. Schedule is subject to approval by NSF/MEXT.

ICDP – Project Schedule http://www.icdp-online.org/project/project.html

	ICDP Projects	Drilling Dates	Location
1	San Andreas Fault Zone Observatory at Depth	Jun. '02–Oct. '07 **	Parkfield, Calif., U.S.A.
2	Hawaii Scientific Drilling Project	Oct. '04–Dec '06	Hilo, Hawaii, U.S.A.
3	Drilling Active Faults in South African Mines	Jan. '05–Jun. '06 *	Witwatersrand, South Africa
4	Lake El'gygytgyn Drilling Project	sched. for '06–'07	Lake El'gygytgyn, Russia
5	Iceland Deep Drilling Project	sched. for '06–'10	Reykjanes, Iceland
6	Fennoscandian Arctic Russia-Drilling Early Earth Project	sched. for May–Oct. '07	Russia
7	New Jersey Continental Shelf	sched. for Jun. '07	New Jersey, U.S.A.

* Subsequent Borehole Monitoring
** Subsequent Borehole Monitoring until 2020