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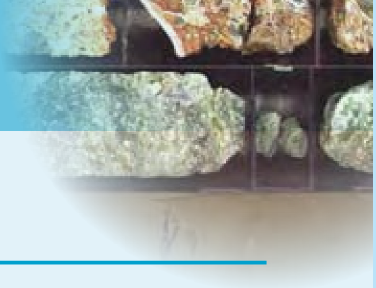
Editorial Preface



Dear Reader:

The start of scientific ocean drilling dates back almost 50 years to the project 'Mohole'. This project was an ambitious enterprise to drill 6–7 km below the seafloor to sample the seismic Mohorovicic discontinuity ('Moho') underlying Earth's crust. Technologically much ahead of its time and financially troubled, the project Mohole was dissolved in 1966. A significant outcome of the project was, however, that it demonstrated potential for high scientific return, and thereby set the stage for decades of successful scientific ocean drilling, with international continental drilling (ICDP) following suit in 1996.

Recent IODP expeditions (page 4) moved us one small but important step closer to the original goal of project Mohole by penetrating the entire upper oceanic crust. A recent workshop white paper (page 11) concluded that the goal of getting to the base of the oceanic crust and into the underlying mantle remains unchanged. Obviously, the scientific questions posed today are more refined and focus more on matters related to 'why' and 'how' and less on 'what is Moho'.

Continental and ocean drilling provide extremely important and complementary tools for advancing our knowledge base and understanding of how humankind can be affected at various timescales by Earth processes and climatic change. A workshop held in 2006 addressed ambitious land–sea transect drilling across the Chicxulub bolide impact crater and may later result in future joint operations (page 42). The application of land and marine drilling to assess the volcanic risks to densely populated areas was discussed in a recent workshop in Naples (page 48). Together with these examples, preliminary results from continental drilling of a reference section of oceanic anoxic event 2 (page 19) demonstrate the strong thematic alignment of continental and ocean drilling: It is all about how the planet works.

ICDP and IODP scientists take this message to heart and currently investigate options for the most seamless interface between the two programs. Coordinated core and sample access, uniform site descriptions, data access, and joint evaluation of scientific proposals are areas under consideration. In addition, a joint effort to complete a land-sea drilling transect across the New Jersey margin is scheduled for 2007. These initiatives not only improve the research opportunities for the present scientific community, but will also help us to speak with one voice in assuring that international scientific drilling continues to remain an active and exciting venue for researchers in the study of our planet.

Hans Christian Larsen
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Editor

Front cover: Comparison of damaged and new coring bits. The damaged bit lost three cones and most of the fourth one while coring extremely hard recrystallized dikes during IODP Expedition 312. Read more on page 4. **Left inset:** Lake Van, Turkey. Pre-site survey 2004: UWITEC coring platform (see page 40).

Scientific Drilling

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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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IODP Expeditions 309 and 312 Drill an Intact Section of Upper Oceanic Basement into Gabbros

by Jeffrey C. Alt, Damon A.H. Teagle, Susumu Umino, Sumio Miyashita, Neil R. Banerjee, Douglas S. Wilson, the IODP Expeditions 309 and 312 Scientists, and the ODP Leg 206 Scientific Party

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Summary

The Integrated Ocean Drilling Program's (IODP) Expeditions 309 and 312 successfully completed the first sampling of an intact section of upper oceanic crust, through lavas and the sheeted dikes into the uppermost gabbros. Hole 1256D, which was initiated on the Ocean Drilling Program's (ODP) Leg 206, now penetrates to >1500 mbsf and >1250 m sub-basement. The first gabbroic rocks were encountered at 1407 mbsf. Below this, the hole penetrates ~100 m into a complex zone of fractionated gabbros intruded into contact metamorphosed dikes.

Deep Drilling of the Ocean Basement

Drilling a complete *in situ* section of ocean crust has been an unfulfilled ambition of Earth scientists since the inception of ocean drilling that followed the audaciously ambitious Project MoHole, which was targeted to sample the first order seismic boundary named the Mohorovičić discontinuity ('Moho'; see Bascom, 1961; Greenberg, 1974). The principal emphasis of Project MoHole was to understand the nature of the oceanic crust and the underlying uppermost mantle thought to be separated by the Moho at roughly 6 km depth below the ocean basins. Unfortunately, many of the key questions regarding the formation and evolution of the oceanic crust remain unanswered despite a further forty years of research; moreover, our sampling of the ocean crust remains extremely cursory (see compilations in Teagle et al., 2004; Wilson et al., 2003). Although offset drilling strategies, where deeper parts of the ocean crust are sampled by drilling in tectonic windows, have had notable success (e.g., Hess Deep, ODP Leg 147; Southwest Indian Ridge, ODP Leg 176; Mid-Atlantic Ridge, Ildefonse et al., 2006), composite sections of the ocean crust are not substitutes for long continuous drill holes into intact crust far from fracture zones. Before the recent success of drilling at Site 1256, only Hole 504B, located in 6.9-Ma old crust on the southern flank of the intermediate spreading rate Costa Rica Rift, had sampled through the lava-dike transition (Alt et al., 1996). However, the sheeted dike-gabbro transition had never been drilled, even though it is critical to deciphering crustal accretion processes at mid-ocean ridges.

The IODP Expeditions 309 and 312 therefore tackled a major unfulfilled goal of ocean drilling—namely the sampling of a complete section from lavas, through the dikes, and into gabbros. This was accomplished by drilling Hole 1256D in crust that formed at a superfast spreading rate at the East Pacific Rise ~15-My ago (Fig. 1). This approach exploits the apparent inverse relationship between the depth of axial low velocity zones, hypothesized to be magma chambers, and spreading rate (Fig. 2). Drilling took place on three scientific ocean drilling cruises: ODP Leg 206 (Wilson et al., 2003) and IODP Expeditions 309 and 312 (IODP Expedition 309 Scientists, 2005; IODP Expedition 309/312 Scientists, 2006; Teagle et al., 2006; Wilson et al., 2006). IODP Expedition 312 was the last cruise of IODP Phase I and the final scientific drilling voyage of *JOIDES Resolution* before major refitting and renaming. The successful accomplishment of the

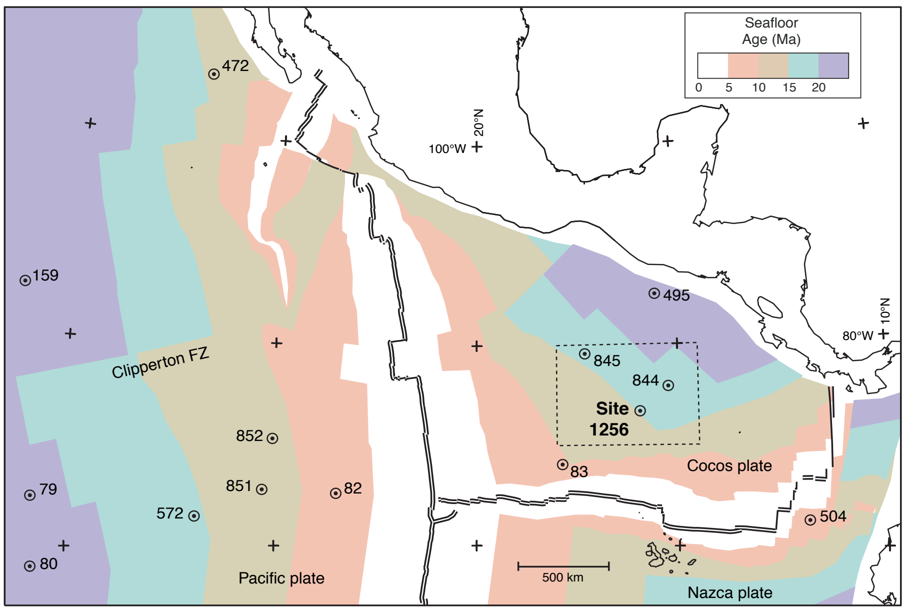

Figure 1. Age map of the Cocos plate and East Pacific Rise with isochrons at 5-My intervals, converted from magnetic anomaly identifications according to timescale of Cande and Kent (1995). The wide spacing of 10–20 Ma isochrons to the south reflects the extremely fast (200–220 mm yr^{-1}) full spreading rate. The locations of deep drill holes into the oceanic crust at Sites 1256 and 504 are shown.

longstanding scientific ocean drilling ambition of coring to gabbros *in situ* is a fitting finale to the *JOIDES Resolution*'s achievements and to Phase I of IODP.

Goals of IODP Expeditions 309 and 312

Deep basement drilling at Site 1256 had four principal scientific objectives:

1. Test the prediction that gabbros representing the crystallized melt lens should be encountered at a depth of 900–1300 m subbasement at Site 1256 from the correlation of spreading rate with decreasing depth to the axial melt lens
2. Determine the lithology and structure of the upper oceanic crust for the superfast spreading end-member
3. Correlate and calibrate remote geophysical seismic and magnetic imaging of the structure of the crust with basic geological observations
4. Investigate the interactions between magmatic and alteration processes, including the relationships between extrusive volcanic rocks, the feeder sheeted dikes, and the underlying gabbroic rocks.

Highlights of Deep Drilling in Hole 1256D

ODP Leg 206 installed a reentry cone supported by 20-inch casing with a large-diameter (16-inch) casing that sealed off the 250-m sediment blanket and cemented 19 m into the basement. Using the large-diameter casing left open the possibility that additional casing strings could be installed if future expeditions decided to isolate eroded portions of the hole. Leg 206 then deepened the hole through 502 m of massive lavas and sheet flows with moderate to high recovery (48%; Wilson et al., 2003). IODP Expeditions 309 and 312 deepened Hole 1256D by 755.1 m to 1507.1 mbsf (Fig. 3). The uppermost basement comprises a ~100-m-thick sequence of lava dominated by a single flow up to 75 m thick, requiring at least that much seafloor relief to pool the lava. On modern fast spreading ridges, such topography does not normally develop until 5–10 km from the axis. The lavas immediately below include sheet and massive flows and minor pillow flows. Sub-vertical, elongate, flow-top fractures filled with quenched glass and hyaloclastite in these lavas indicate flow lobe inflation requiring eruption onto a sub-horizontal surface off-axis (Umino et al., 2000). Thus, we estimate a total thickness of 284 m for off-axis lavas, close to the assumed thickness. Sheet flows and massive lavas that erupted at the ridge axis make up the remaining extrusive section down to 1004 mbsf, before a lithologic transition is marked by sub-vertical intrusive contacts and mineralized breccias. Below 1061 mbsf, subvertical intrusive contacts are numerous, indicating the start of a relatively thin (~350-m-thick) sheeted dike complex that is dominated by massive basalts. Some basalts have doleritic textures, and many are cut by sub-vertical dikes with common strongly brecciated and mineralized chilled margins. There is no

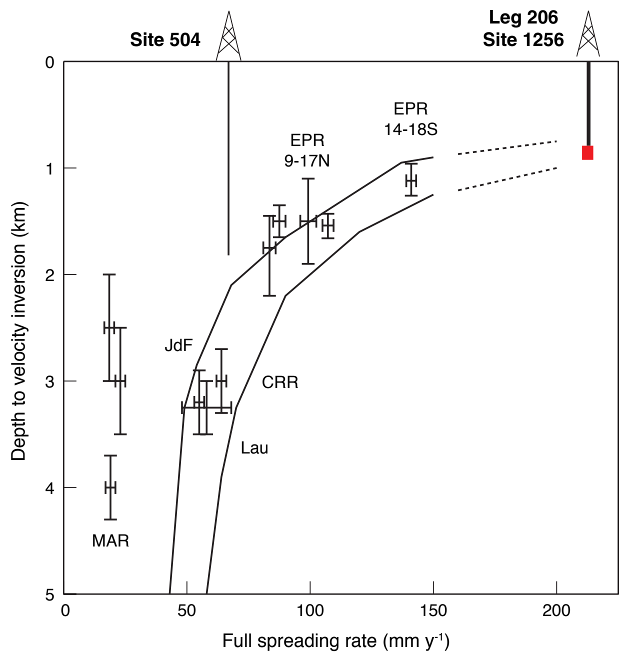

Figure 2. Depth to axial low-velocity zone plotted against spreading rate (modified from Carbotte et al. (1997). Depth versus spreading rate predictions from two models of Phipps Morgan and Chen (1993) are shown, extrapolated subjectively to 200 mm y^{-1} (dashed lines). Penetration to date in Holes 504B and 1256D is shown by solid vertical lines, with the depth at which gabbros were intersected indicated by the red box. Following core descriptions, a thickness of ~300 m of off-axis lavas is shown for Hole 1256D and assumed for Hole 504B. EPR = East Pacific Rise, JdF = Juan de Fuca Ridge, Lau = Valu Fa Ridge in Lau Basin, CRR = Costa Rica Rift.

evidence from core or from geophysical wireline logs for significant tilting of the dikes. This is consistent with seismic reflection images of sub-horizontal reflectors in the lower extrusive rocks that are continuous for several kilometers across the site (Hallenborg et al., 2003).

There is a stepwise increase in alteration grade downward from lavas into dikes, with low temperature phases (<150°C; phyllosilicates, iron oxyhydroxides) in the lavas giving way to dikes partially altered to chlorite and other greenschist minerals (at temperatures greater than ~250°C; Fig. 3). Within the dikes the alteration intensity and grade increase downward, with actinolite more abundant than chlorite below 1300 mbsf and with hornblende present below 1350 mbsf. These results indicate temperatures approaching ~400°C. The dikes have significantly lower porosity (mostly 0.5%–2%) and higher P-wave velocities and thermal conductivity than the lavas, and porosity decreases while P-wave velocity increases with depth in the dikes. In the lower ~60 m of the sheeted dikes (1348 to 1407 mbsf), basalts are partially to completely recrystallized to distinctive granoblastic textures resulting from contact metamorphism by underlying gabbroic intrusions (Fig. 4).

Gabbro and trondhjemite dikes intrude into sheeted dikes at 1407 mbsf, marking the top of the plutonic complex. Two major bodies of gabbro were penetrated beneath this contact, with the 52-m-thick upper gabbro separated from the 24-m-thick lower gabbro by a 24-m screen of granoblastic dikes (Fig. 4). The upper gabbro comprises gabbros, oxide gabbros, quartz-rich oxide diorites and small trondhjemite dikelets. These rocks are moderately to highly altered by hydrothermal fluids to actinolitic hornblende, secondary plagioclase, epidote, chlorite, prehnite, and laumontite. The intensity of hydrothermal alteration increases with grain size and proximity to intrusive boundaries.

The lower gabbro comprises gabbro, oxide gabbro, and subordinate orthopyroxene-bearing gabbro and trondhjemite that are similarly altered. It also has clear intrusive contacts with the overlying granoblastic dike screen. Partially resorbed, stoped dike clasts are entrained within both the upper and lower margins of the lower gabbro (Fig. 4G). The lowermost rock recovered from Hole 1256D is a highly altered actinolite-bearing basaltic dike that lacks granoblastic textures, and is therefore interpreted to be a late dike that post-dates the intrusion of the lower gabbro.

Contrary to expectation, porosity increases and P-wave velocities decrease stepwise downward from lowermost dikes into the uppermost gabbro at Hole 1256D, as a result of the contact metamorphism of the granoblastic dikes and the strong hydrothermal alteration of the uppermost gabbros (Fig. 3). Porosity and velocity then increase downhole in the gabbro but are still <6.5 km s^{-1}.

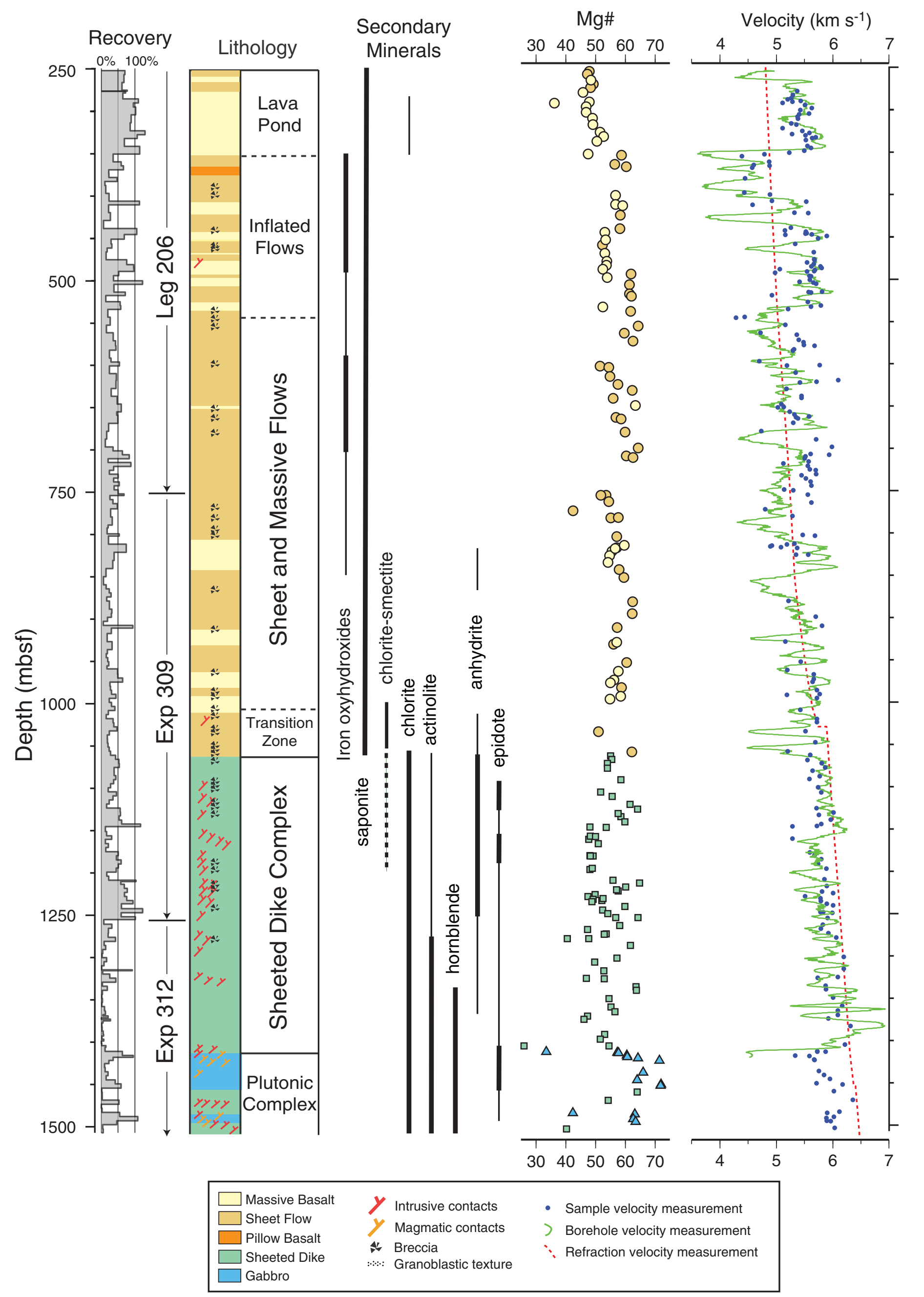

Figure 3. Summary lithostratigraphic column of the basement drilled to date at Site 1256 showing recovery, major lithologies, downcore index alteration, mineral distribution (thick lines = abundant; thin lines = rare), downcore distribution of Mg-number (where Mg# = 100 ° - Mg/ (Mg + (0.9 x Fe)) atomic ratio), and seismic velocity measured on discrete samples, wireline tools, and seismic refraction (from Wilson et al., 2006).

Flows and dikes from Hole 1256D show a wide range of magmatic fractionation, from fairly primitive to evolved (Figs. 3 and 5). Shallower than 600 mbsf, magma compositions are bimodal, with relatively evolved thick flows and more primitive thin flows. Primitive and evolved compositions are closely juxtaposed within the dikes, as would be expected for vertically intruded magmas. For most major elements and many trace elements, the range of concentrations in flows and dikes is similar to that observed for the northern East Pacific Rise (EPR, e.g., Fig. 5). A few incompatible elements, including Na and Zr, have lower concentrations than observed for the modern EPR lavas, but the general overlap of compositions indicates similar processes at the superfast spreading ridge that formed Site 1256 and the modern EPR. The gabbro compositions span a range similar to the flows and dikes, but are on average more primitive. Even though less fractionated, the average gabbro composition is evolved relative to candidates for primary magma in equilibrium with mantle olivine. Therefore, the residue removed from primary magma to produce the observed gabbro and basalt compositions must be deeper than the uppermost gabbros penetrated in Hole 1256D.

Conclusions from Site 1256

The ocean crust is subdivided into three seismic layers: layer one comprises sediments and has low velocity; layer two has low velocity and a high velocity gradient; layer three is characterized by high velocity (at least 6.7 km s^{-1}) and low gradient. There is a widespread perception that layer three is equivalent to gabbro, even though Hole 504B has penetrated that layer but not gabbro (Alt et al., 1996). Seismic velocities of discrete shipboard samples and from wireline tools indicate velocities for gabbro in Hole 1256D are <6.5 km s^{-1} and do not fit models for layer three. Further drilling in Hole 1256D, however, could recover samples to characterize the transition between seismic layers.

Site 1256 has a relatively thick lava sequence and a thin dike sequence. The thick lava sequence with many massive flows is interpreted as a consequence of short vertical transport distance from the shallow magma chamber. There is little evidence for tilting (at most a few degrees) in Hole 1256D and no evidence for significant faulting. The ponded flow at Site 1256, however, indicates that faults of ~50–100 m offset must exist in superfast crust to provide the necessary relief for ponding of the flow.

When intruded as a magma, the upper gabbro in Hole 1256D would likely have had depth and impedance properties consistent with the geophysically imaged melt lenses at mid-ocean ridges. However, this gabbro body is chilled against the underlying dike screen, which precludes segregating a crystal residue that subsides to form the lower crust as in the gabbro glacier model. Thus, sills or other bodies containing cumulate materials must exist deeper in the crust or underlying mantle, but could be as shallow as just below the present maximum depth of Hole 1256D.

The ~800-m-thick lava sequence is generally less hydrothermally altered than other basement sites (Wilson et al., 2003), and the distributions of secondary

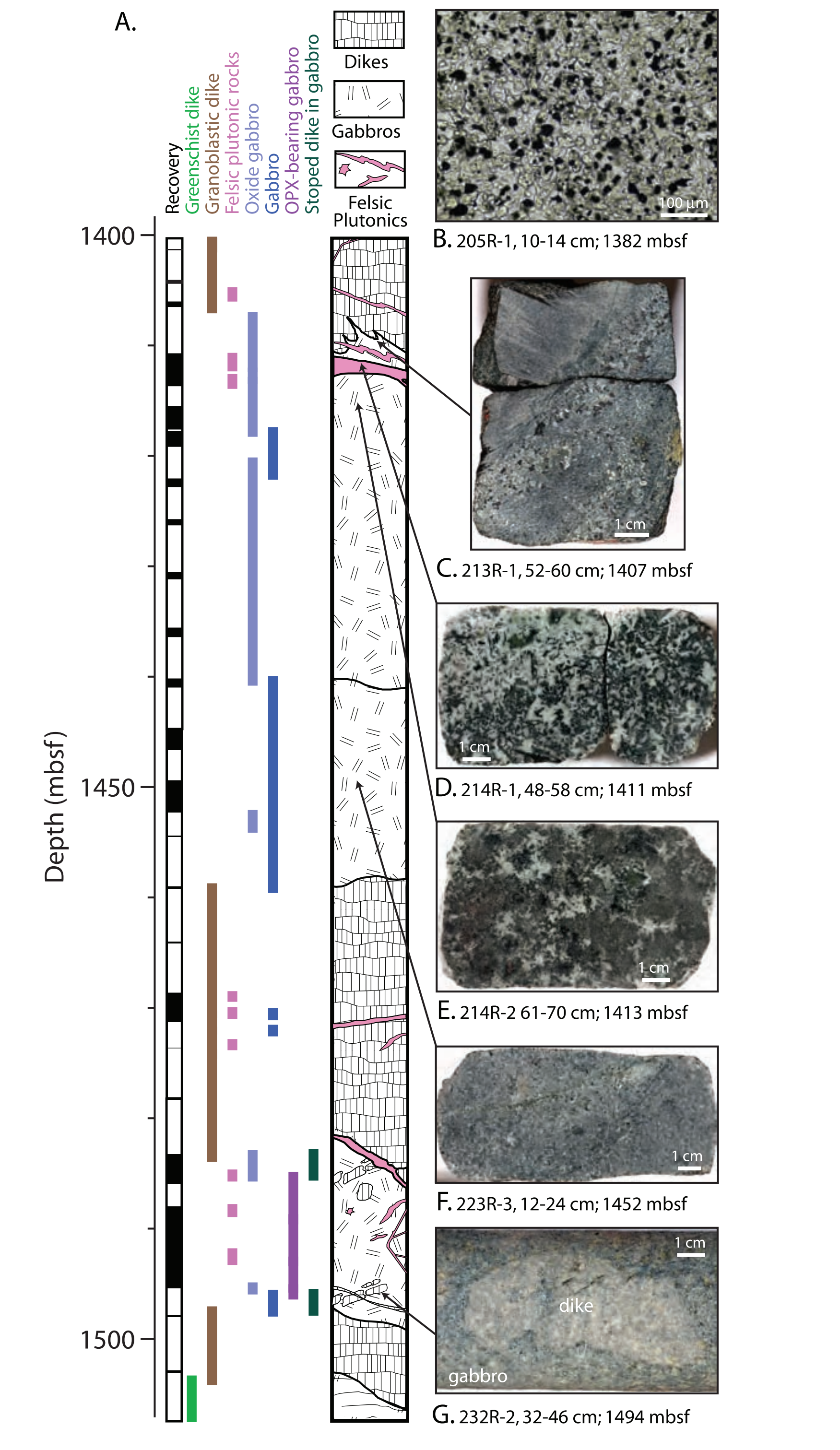

Figure 4. [A] Schematic lithostratigraphic section of the plutonic complex from the lower portion of Hole 1256D with representative photographs of key samples. The distribution of rock types is expanded proportionately in zones of incomplete recovery. Felsic plutonic rocks include quartz-rich oxide diorite and trondjhemite. [B] Photomicrograph of a dike completely recrystallized to a granoblastic association of equant secondary plagioclase, clinopyroxene, magnetite, and ilmenite. Some granoblastic dikes have minor orthopyroxene. [C] The dike-gabbro boundary! Medium-grained oxide gabbro is intruded into granoblastically recrystallized dike along an irregular moderately dipping contact. The gabbro is strongly hydrothermally altered. [D] Quartz-rich oxide diorite strongly altered to actinolitic hornblende, secondary plagioclase, epidote, and chlorite. Epidote occurs in ~5-mm clots in the finer grained leucocratic portions of the rock. [E] Disseminated oxide gabbro with patchy texture and cm-scale dark ophitically intergrown clinopyroxene and plagioclase patches separated by irregular, more highly altered leucocratic zones. [F] Medium-grained strongly hydrothermally altered gabbro. The sample is cut by several chlorite and actinolite veins with light gray halos. Plagioclase is replaced by secondary plagioclase and clinopyroxene by amphibole. [G] Clast of partially resorbed dike within gabbro. (photos from Wilson et al.).

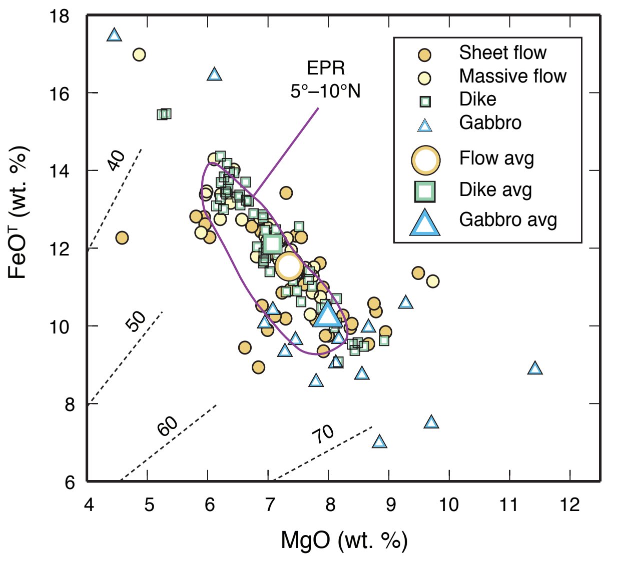

Figure 5. FeO^T (Total Fe expressed as FeO) vs. MgO for the basement at Site 1256, compared with analyses of northern EPR. Dashed lines show constant Mg number. Possible primary mantle melt compositions should have Mg number of 70–78 and MgO of 9–14 wt. %. All flows and dikes and most gabbros are too evolved to be candidates for primary magmas (from Wilson et al., 2006).

minerals indicate a structural control of alteration rather than simply decreasing seawater influence downward. There is a stepwise increase in alteration temperatures downhole, from ~100°C in the lavas to ~250°C in the uppermost dikes. Aside from the granoblastic contact metamorphic assemblages in the basal dikes, hydrothermal mineralogy and inferred alteration temperatures of the lower dikes in Hole 1256D are generally similar to those in the lower dikes of Hole 504B (up to ~400°C). The much thinner dike section at Site 1256 than at Site 504 (~350 vs. ~1000 m), however, indicates a much steeper hydrothermal temperature gradient at Site 1256 (~0.5°C m^{-1} vs. 0.16°C m^{-1} in 504B).

Epidosites (equigranular epidote-quartz-titanite rocks) delineate zones of upwelling black smoker-type fluids around the dike-gabbro boundary in ophiolites. Although epidote is common within and below the transition zone in Hole 1256D (Fig. 3), epidosites were not encountered. Anhydrite precipitation must play a critical, but so far poorly understood, role in oceanic hydrothermal circulation. Anhydrite in Hole 1256D (Fig. 3) is more abundant than in Hole 504B, but it is still present in much lower quantities than predicted by models of hydrothermal circulation.

Technical Challenges

Even coring basement to more typical depths of a few hundred meters can run into technical problems, so coring to more than 1 km subbasement and through particularly hard dike formations presented challenges. Figure 6 shows drilling progress versus time at Site 1256. The first challenge (the flat portion of the depth vs. time line at the top of Hole 1256D in Fig. 6) was the installation of the large-diameter (20-inch) casing through sediment, then the drilling out of a 21-inch hole in basement below the 20-inch casing in order to accept the 16-inch basement casing. This required the use of a bi-center reamer, which has an 18-inch pass-through diameter that allows this hardware to fit through the 20-inch casing. During drilling, the actual diameter of the cut hole is 21 inches. This was the first time such a device was used in scientific ocean drilling.

At ~900 mbsf during Leg 309 (Fig. 6), the driller noted a loss of pump pressure, so the drill string was pulled. A horizontal gash was discovered that had nearly severed the bit sub (Fig. 7). A second torsional failure of the drill string occurred in the 5-inch pipe above the bit sub. Such a failure of the bit sub-assembly had not been witnessed before in the shipboard memory of scientific ocean drilling, and the rapid diagnosis and response of the Transocean operations team certainly averted a costly and time-consuming major equipment loss in Hole 1256D.

Coring in the very hard recrystallized lower dikes proceeded slowly, and at 1372.8 mbsf with generally good drilling conditions, the fifth coring bit of IODP Expedition 312 failed (Figs. 6 and cover picture). Cleaning out the metal debris from the bottom of the hole required four fishing round trips (two with a fishing magnet and two with a mill) before coring could be confidently resumed. Despite these

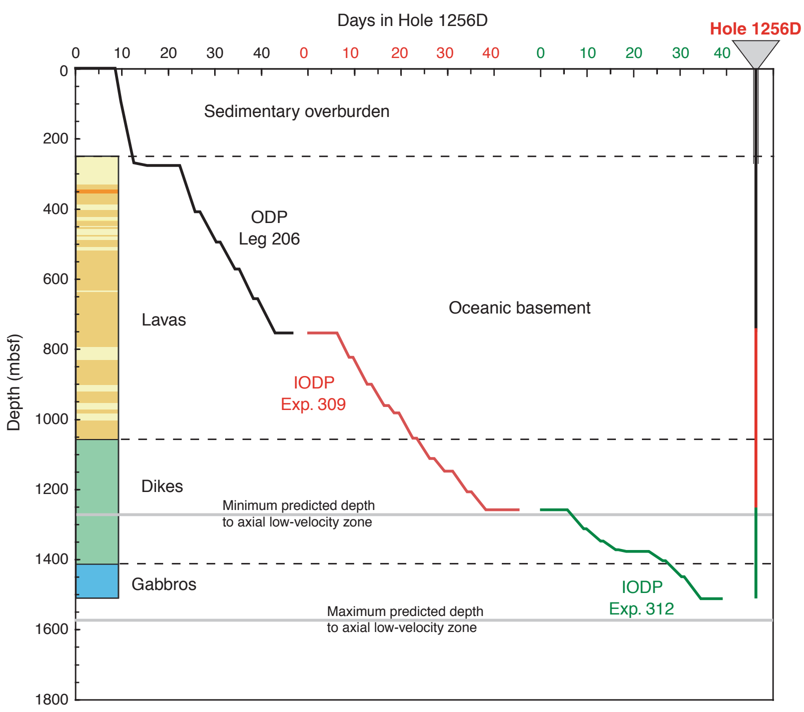

Figure 6. Drilling progress versus time in Hole 1256D.

technical challenges, the major operational goal of the expeditions, coring into gabbro, was successfully achieved.

Goals of Future Drilling at Site 1256

Although the major objective of penetrating into gabbro was achieved, critical scientific questions remain to be answered. These include the following: 1) Does the lower crust form by the recrystallization and subsidence of a high level magma chamber ("gabbro glacier"), or by crustal accretion from intrusion of sills throughout the lower crust? 2) Is the plutonic crust cooled by conduction or hydrothermal circulation? 3) What is the geological nature of layer three and the layer two/three boundary at Site 1256? 4) What is the magnetic contribution of the lower crust to marine magnetic anomalies? Hole 1256D is poised at a depth where samples that would conclusively address these questions could be obtained, possibly with only a few hundred more meters of drilling. What is important is that the hole is clear of debris and open to its full depth. Increased rates of penetration (1.2 m h^{-1}) and core recovery (>35%) in the gabbros indicate that a return to Hole 1256D could deepen the hole at least a further 500 m into plutonic rocks, past the present transition from dikes to gabbro, and into a region of solely gabbroic rocks.

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Figure 7. Torsional failure of the bit sub during Expedition 309. A horizontal gash opened for ~150° (11 inches) of the circumference of the 3⁄4-inch thick bit sub wall, ~15 inches from the bit, with more ragged fracture tips propagating a further ~75° around the pipe from each end of the clean fracture. When in tension with the drill bit hanging from the sub, the fracture opened up to 1 cm, and the bit was held on by only ~4.25 inches of the bit sub wall.

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Mission Moho Workshop: Drilling Through the Oceanic Crust to the Mantle

by Benoit Ildefonse, David M. Christie, and the Mission Moho Workshop Steering Committee

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Introduction

The Mohorovičić discontinuity (Moho) is a seismically imaged, first order acoustic interface assumed to represent the transition between the Earth's crust and the underlying mantle in both continental and oceanic settings. To date, this elusive frontier has been a symbolic goal for many geologists, but beyond the reach of available drilling technology. With the recent commissioning of the *Chikyu,* a new riser-drilling vessel of the Integrated Ocean Drilling Program (IODP), the technically challenging goal of drilling to and through the Moho within the ocean basins becomes feasible.

The formation and evolution of the oceanic lithosphere are the dominant processes in the chemical differentiation and physical evolution of our planet. This evolution encompasses the transfer and transformation of material and energy from Earth's mantle to the crust, and from the crust to the ocean and atmosphere. Independent of sunlight, the evolving ocean crust supports life in unique subsurface and seafloor habitats that may resemble the earliest of Earth's ecosystems. From its formation until its return by subduction to the mantle, the oceanic lithosphere interacts with seawater, sequesters surface materials (including water), and recycles them back into the mantle.

In April 1961, the first successful drilling and coring of oceanic basement recovered a few meters of basalt in 3800 meters water depth offshore Guadalupe Island, Mexico. This remarkable breakthrough was the first stage of Project Mohole, a much more ambitious project to drill through the ocean crust to the Moho (e.g., Bascom, 1961; Shor, 1985). Over the last 45 years, this fundamental goal has not been achieved, but it has been consistently reiterated in the successive plans of the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), and the IODP.

Since the end of the 1960s, tens of holes have been drilled and cored into oceanic basement (Fig. 1). These have led to major improvements in our understanding of oceanic crustal architecture and of mid-ocean ridge processes (Dick et al., 2006; Ildefonse et al., 2007). To date, however, only four deep basement holes have penetrated more than 1000 meters into oceanic basement (Fig. 2). IODP's most recent successes in this arena are two deep holes at complementary sites. Hole U1309D, in slow-spread Atlantic Ocean crust, reached 1415 m below sea floor and recovered a complex series of gabbroic rocks (Blackman et al., 2006; Ildefonse et al., 2006); and Hole 1256D, in the superfast-spread crust of the eastern Pacific Ocean, reached 1507 m below seafloor and, for the first time, passed through a complete Layer 2 (pillow basalt and sheeted dike) sequence into the transition between sheeted dikes and underlying gabbros (Wilson et al., 2006; Alt et al., in press). These two holes have provided considerable experience in deep ocean crustal drilling, complementing that from the two earlier deep and successful ODP Holes

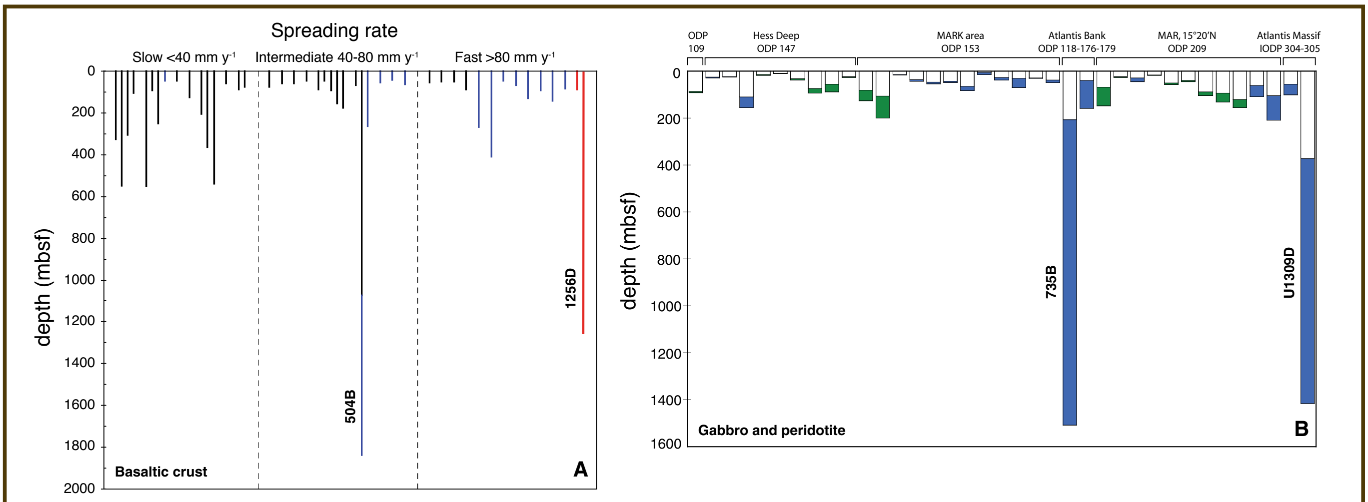

Figure 1. Summaries of existing scientific drill holes into oceanic crustal and mantle rocks. [A] Depth of penetration for all holes penetrating more than 50 meters into basaltic basement, as a function of spreading rate. Hole 1256D has reached the base of the sheeted dike complex at a shallower depth than the bottom of Hole 504B, which is still in sheeted dikes. Black = DSDP holes, blue = ODP holes, red = IODP holes. Modified from IODP Expeditions 309 and 312 scientists (2006). [B] Depth of penetration for all ODP and IODP holes deeper than 10 meters below seafloor into gabbroic rocks or residual mantle peridotite. Blue = dominantly gabbro, green = dominantly peridotite, white = no recovery. After Blackman et al. (2006).

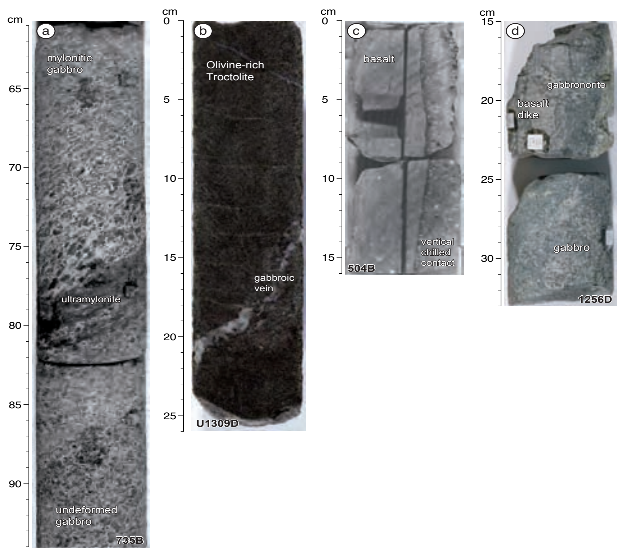

Figure 2. Core pieces from the four deepest holes in the ocean crust. [A] The gabbroic section recovered in Hole 735B (Atlantis Bank, Southwest Indian Ridge; Dick, et al., 1999) is unique in that as much as 23% of the core is plastically deformed. The picture shows the base of a ~20-meters-thick shear zone at ~964 m below seafloor. [B] Olivine-rich troctolite from Hole U1309D (Atlantis massif, Mid-Atlantic Ridge; Blackman, et al., 2006) at ~1194 m below seafloor. These troctolites contain as much as 90% olivine, and are locally extremely fresh (<1% serpentinization). [C] Hole 504B (Guatemala basin, Eastern Pacific) sampled for the first time the *in situ* sheeted dike complex, as illustrated by this sample of a vertical chilled contact between two basaltic dikes recovered at ~1352.9 m below seafloor (Becker, Sakai et al., 1988). [D] The transition zone from sheeted dikes to gabbro was reached for the first time in Hole 1256D (Expedition 309 and 312 Scientists, 2006). The picture shows the contact between basaltic dike and gabbro units at ~1488 meters below seafloor. The basalt is invaded by gabbronorite from the gabbro unit.

504B and 735B in the eastern Pacific Ocean (Guatemala Basin) and Indian Ocean, respectively.

The Mission Moho workshop, was convened in Portland, Oregon (7–9 September 2006) to provide an opportunity for the scientific community to define the scientific goals for deep crustal drilling, to propose elements of a global strategy, and to develop community priorities in pursuit of IODP's 21st Century Mohole Initiative—"to advance significantly our understanding of the processes governing the formation and evolution of oceanic crust" (IODP Initial Science Plan, International Working Group, 2001). The workshop focused on the development of a scientific and operational framework that can guide an IODP Mission Moho for a decade or longer. An important part of this framework is to identify the scientific and engineering objectives that can be addressed immediately with available technology, while leading us toward the ultimate "Mohole"—a complete *in situ* section through the ocean crust—at a later stage.

The Journey to the Moho: Formation and Architecture of the Ocean Crust

Since the early 1970s, the standard model of a uniformly layered ocean crust has evolved significantly. Ocean drilling and other marine geological and geophysical data have demonstrated a spatially highly variable crustal architecture to be present. Ocean crust produced at fast spreading ridges is believed to be close to the layered "Penrose" stratigraphy developed from ophiolites (Penrose conference participants, 1972; Fig. 3). That is, it appears to be uniformly layered and fairly homogeneous, reflecting a relatively uniform mode of accretion (e.g., Macdonald et al., 1984; Detrick et al., 1993; Hooft et al., 1996).

In contrast, crust created at slow and ultra-slow spreading ridges is spatially heterogeneous over distances as small as a few hundred meters, both along and across isochrons. Along parts of slow spreading ridges (for example, the centers of ridge segments in the northern Atlantic), magmatic processes dominate, and recent seismic imaging has for the first time revealed a magma chamber beneath the Mid-Atlantic Ridge at 37°18'N (Singh et al., 2006). This result tends to support the hypothesis that such magmatically robust, slow-spread segments are fundamentally similar to those of fast spreading ridges. However, this similarity is limited in space, and the architecture of the crust accreted at slow-spreading ridges typically changes along-axis toward segment ends, where it is more heterogeneous and even discontinuous, with a mixture of serpentinized peridotite and gabbroic intrusions locally capped by lavas with or without intervening sheeted dikes (Fig. 4; Cannat, 1993). This lateral and vertical variability has been well-documented through seafloor geological studies and geophysical surveys, in addition to scientific ocean drilling expeditions (e.g., Karson and Elthon, 1987; Dick, 1989; Cannat et al., 1995, 2006; Canales et al., 2000; Kelemen, Kikawa, Miller, et al., 2004).

<u>*The direct route to the Moho:*</u> There was a clear workshop consensus that the first priority for a Mission Moho should be a deep, full crustal penetration hole through the Moho and into the uppermost mantle at a single site and that the first full-penetration hole should be in fast-spread ocean crust. Although only about 20% of modern ridges are spreading at fast (>80 mm yr^{-1}) rates, fully half of the present day ocean crust, equivalent to ~30% of the Earth's surface, was produced at fast spreading centers. In other words, most of the crust recycled into the mantle at subduction zones during the last ~200 My formed at fast spreading centers. Hence, an understanding of accretion processes at one deep drilling site might reasonably be extrapolated to describe a significant portion of the Earth's surface.

Drilling and sampling a complete crustal section will enable scientists to accurately estimate the bulk composition of the crust; understand the extent and intensity of hydrothermal exchange between the ocean crust and seawater; establish the chemical connections between the lavas that erupt at the seafloor and the melts that are separated from their mantle sources; more accurately estimate the chemical flux returned to the mantle by subduction; test competing models of lower crustal magmatic accretion; calibrate regional seismic measurements and the layered-crust models

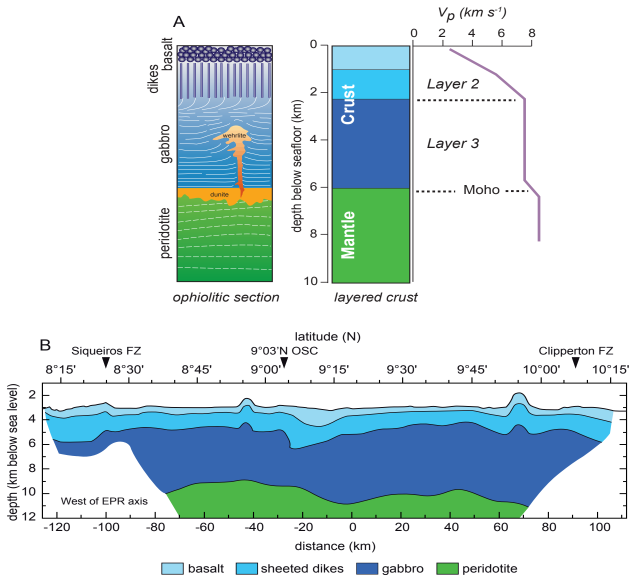

Figure 3. Sections through typical fast-spread crust. [A] Comparison of the layered stratigraphy derived from seismic data (right column; modified from Mével, 2003), and diagrammatic representative lithostratigraphy of the Oman ophiolite sections (Nicolas, 1990). [B] Interpreted lithostratigraphy of East Pacific Rise crust, from a ridge -parallel wide-angle seismic refraction profile between 8°N and 10°N, immediately west of the ridge axis (after Canales et al., 2003).

derived from them; better understand the origin of magnetic anomalies; and determine cooling rates of the lithosphere. Only by sampling across the crust-mantle boundary will we be able to define, at least in one place, the geological meaning of the Moho, determine the *in situ* composition of the uppermost mantle and its deformation, and address details of the physics and chemistry of mantle melt migration.

Essential complementary studies: The fundamental objective of fully penetrating the crust in at least one place must be supplemented by studies of spatial and temporal variability if a comprehensive understanding of the origin and evolution of the ocean lithosphere is to be achieved. In order to fully understand the architecture of the ocean crust, the slow-spread crust must be explored in different tectonic settings. For example, serpentinized mantle rocks are commonly incorporated into the crust (as defined seismically) at slow-spreading ridges. Drilling in this type of crust down to fresh peridotite will test competing hypotheses on the nature of the Moho. Is the Moho (1) the boundary between the residual upper mantle and the igneous crust, or (2) a broader zone of layered ultramafic and mafic rocks, or (3) a serpentinization front, or, perhaps, (4) some combination of these three? Slow-spread crust also offers windows of opportunity to relatively easily acquire long sections of lower crust (e.g., IODP Sites 735 and U1309).

The overarching goals of deep crustal drilling in slow-spread lithosphere are to efficiently characterize the spatial and temporal variability of crustal and upper mantle architecture, and to identify and constrain the key forcing functions that control this variability. To achieve these goals will require drilling to various depths at key sites that encompass much of the known vertical and lateral variability of slow-spread crust. Main objectives for this type of drilling, in addition to those listed above for the deep penetration of the crust, include:

- Determining the variability of the lithologic nature of the (seismic) Moho.
- Investigating the contrast between crust formed along volcanogenic parts of slow spreading ridges (segment centers) and lava-poor segment ends. Is crust from segment centers similar in structure to fast-spread crust ?
- Understanding the relationships between crustal architecture and tectonic setting.
- Determining the depth to which seawater penetrates in different tectonic settings. Is there a relationship between crustal architecture and depth of seawater penetration?
- Investigating the chemical, mineralogical, and microbiological character and variability of hydrothermal systems.

Hydrothermal alteration of the oceanic crust encompasses a wide range of water-rock reactions that change the physical properties of the crust on a variety of temporal and spatial scales. One strategy for studying the aging of oceanic crust is to drill multi-hole transects along seafloor spreading flow lines to examine the time-integrated changes in physical and chemical properties. To date, drilling has been concentrated either relatively close to mid-ocean ridge axes or close to subduction zones; very few holes have been drilled in crust ~20–80 My old. There are, especially, no sites in ~60–65 My- old crust, which, based on heat flow measurements, is the average age at which the crust becomes sealed and the heat flux from the mantle becomes solely conductive. Further, seafloor alteration is spatially heterogeneous and variable in style. Although drilling cannot address this on a global scale, important information on styles and length scales of variability can be obtained by sampling and logging of closely spaced holes in conjunction with cross-hole experiments.

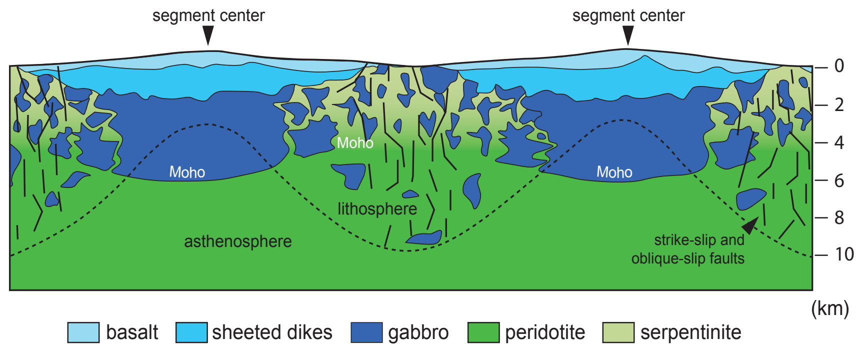

Figure 4. Simplified, interpreted, axis-parallel section through slow-spread crust (modified from Cannat et al., 1995). Note the shallower Moho beneath segment ends, reflecting seismic observations beneath inside high corners along the northern Mid-Atlantic Ridge (e.g., Canales et al., 2000).

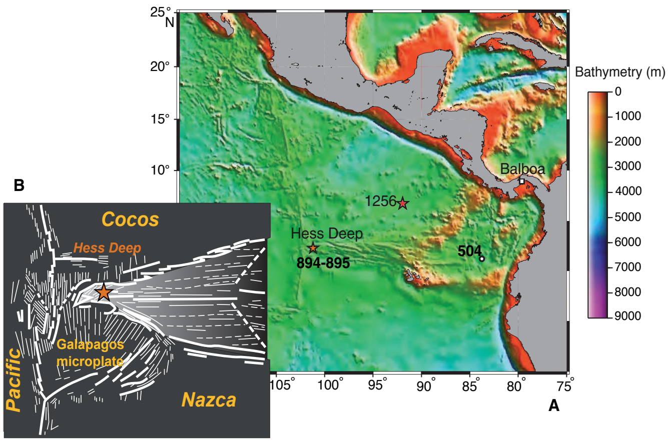

Figure 5. Recommended fast-spread crust sites. [A] Bathymetric map of the eastern Pacific, showing the locations of Site 1256 and Hess Deep (modified from Wilson et al., 2003). [B] Tectonic sketch map of the Pacific-Nazca-Cocos triple junction showing the location of Hess Deep.

The sub-seafloor biosphere also plays an important role in the chemical evolution of oceanic crust. The spatial distribution of microbes in the crust is not known but is likely influenced by host rock composition, temperature, and permeability. Progress in understanding sub-seafloor microbial distribution and its interactions with geochemical alteration processes will proceed hand-in-hand with determining the distribution of rock type, temperature, and permeability as a function of depth and crustal age, and learning how these relationships influence the distribution of microbial activity.

Recommended Elements for Mission Moho

Because of the inherent variability of oceanic lithosphere, a comprehensive program to achieve the scientific objectives outlined above, that is documenting and understanding the evolution of more than half of Earth's surface, is an enormous and complex task. Despite this complexity, and the diversity of individual scientific opinions and priorities, participants reached consensus on the core components of an operationally realistic Mission Moho. Mission Moho should focus on the ultimate goal of achieving full crustal penetration at a single fast-spread site. Progress towards this ultimate goal, both technological and scientific, will require drilling at various additional sites, including some in slow-spread crust.

Complete Crustal Penetration in Fast-Spread Crust: The workshop agreed by consensus that the primary goal of Mission Moho should be to achieve a deep penetration site in fast-spread crust. This would take advantage of the reduced crustal thickness, simpler crustal structure, and representative character of this tectonic setting. Designation of a primary site implies an ongoing commitment to work towards complete penetration through the gabbro of the lower crust into rocks that have mantle seismic velocities and into peridotitic residues of partial melting. Elements of the ongoing scientific drilling effort, which must be coordinated and combined with significant technical development and feasibility testing, will also support a number of science goals, both directly related, and ancillary, to the objective of full crustal penetration.

A few years ago, Site 1256 (Fig. 5A) was chosen to initiate a deep hole in fast-spread crust, starting with ODP Leg 206. This site was selected because it best met a majority of the criteria for a deep penetration site that were thoroughly discussed and listed by the ODP "Architecture of the Lithosphere" Program Planning Group (see the full workshop report, see also see Wilson et al., 2003 for full site justification). Site 1256 is located in the eastern equatorial Pacific, on 15-Ma-old crust of the Cocos plate that formed at a superfast spreading rate (Wilson, 1996). Based on a documented inverse relationship between spreading rate and depth to axial low velocity zones, inferred to be axial melt lenses (Purdy et al., 1992), Site 1256 was selected to provide the best possible chance of reaching gabbroic crust at the shallowest possible depth. After three expeditions (206, 309, and 312), Hole 1256D is currently rooted in a dike-gabbro transition zone (Wilson et al., 2006; Fig. 2D). The gabbros so far have compositions similar to the overlying lavas and dikes. Cumulate rocks have not yet been encountered, and shipboard P-wave velocity measurements are characteristic of seismic layer 2. The current temperature at the bottom of Hole 1256D is estimated as ~115°C–125°C. The Moho is imaged at the site at 5.5 km depth (Wilson et al., 2002).

To achieve full penetration of fast-spread crust, the following steps are recommended.

1. Site 1256 should be designated as the provisional primary site and deepened using current, riserless technology as far possible into gabbro to the point where further riserless drilling is technically not feasible. Further drilling will provide immediate and otherwise unavailable operational experience and fulfill a number of science goals, including confirming whether the hole has fully penetrated into crustal Layer 3.
2. Site identification and survey work should begin as soon as possible to identify and characterize one or more alternative complete crustal penetration site(s), in case conditions at Site 1256 prove to be unsatisfactory for full crustal penetration. The greatest currently perceived threat at Site 1256 is from potentially high down-hole temperatures. For this reason, the alternate site(s) should be on older crust. A critical limiting factor is that the site must be within reach of planned deep riser for the *Chikyu*. This limit is currently 4000 meters. If the design target for the riser could be increased to 4500 meters, the number of potential sites would be significantly higher (Fig. 6). Initial evaluations might encompass two or three sites, with a relatively rapid narrowing to a single site for the more intensive investigations. Activities at such sites might include:

i) site survey activities including seafloor mapping, heat flow, and seismic studies to determine both sediment thickness and seismic structure,
ii) initial shallow drilling to determine the nature of the upper crust and its potential to maintain a stable hole during extended deep drilling operations, and
iii) deeper drilling, ideally at least to the dike-gabbro transition.

3. Additional drilling should be conducted at the primary site to establish spatial context including primary and secondary shallow crustal variability, permeability, and other characteristics.
4. Design work, including necessary technical and engineering development, should begin at the primary site for a deep, cased hole that is engineered for riser drilling through the full crust.
5. Enhanced site survey activities should be conducted at the primary site, including, but not necessarily limited to, high resolution deep seismic studies.

Complementary drilling and context studies in fast-spread crust: Boreholes are spatially limited, and they need to be understood in their broader context. Therefore, it is imperative that any site chosen for a deep penetration hole is thoroughly investigated and characterized. Conceptually, spatial context is also augmented by drilling in tectonic windows and by geological field studies of ophiolites, in particular the Oman ophiolite. Non-riser drilling in tectonic windows can potentially provide access to lower crust and uppermost mantle, the critical boundaries between crustal layers, and, possibly the crust-mantle boundary.

In fast-spread crust, the best known and most readily accessible tectonic window is the Hess Deep rift valley (2°N, 101°W; Fig. 5) near the Pacific-Cocos-Nazca triple junction. Hess Deep is the only place on the Earth's surface where a substantial section of fast-spread lower crust and shallow mantle is exposed at the seafloor and/or accessible via current non-riser drilling technology. Hess Deep is forming as the Cocos-Nazca ridge propagates westward into young (~1 Ma) fast-spread lithosphere generated at the East Pacific Rise. Well-studied exposures of intact upper crust, from the upper gabbros to the lava sequence along the northern scarp, reveal significant lateral variability in crustal structure and hydrothermal alteration (Francheteau et al., 1990; Karson et al., 1992, 2002). Deep crustal and shallow mantle sequences, dismembered by the Cocos-Nazca rifting, are also exposed, from an intra-rift ridge, southward to the axis of the Deep at ~5400 m water depth. Because of these unique exposures, Hess Deep provides a unique opportunity for shallow non-riser drilling to access lower crust and mantle sequences and transitions in fast-spread oceanic crust (Gillis et al., 1993). Complementary studies in this 'natural laboratory' should be among the highest priorities for future investigations.

Complementary drilling in slow-spread crust: The second important goal of Mission Moho is to sample crust and upper mantle produced at low spreading rates (i.e., low magma flux), in order to at least partially address the variability of lithospheric architecture and of the nature of the Moho. Because slow-spread crustal architecture is highly variable, however, there is a broad range of scientific objectives and many drilling options available to address them. The extent to which current or planned drilling projects in slow-spread crust should be included in Mission Moho, and the criteria for inclusion of such projects, will have to be defined by a mission proponent team.

Nevertheless, some key objectives compatible with a Mission Moho emerged from the workshop. One key mission objective, requiring studies at numerous sites, is an assessment of the role of serpentinization in modifying the seismic signature of the ocean crust (e.g., Carlson and Miller, 1997; Mével, 2003) and the transition to typical mantle velocities. Seismic studies will, for the foreseeable future, continue to be the primary tool for investigation of the subsurface over wide areas. Understanding the relationship between lithologic variability and subsurface seismic images is a critical, ongoing goal that can only be reached by drilling multiple sections through non-layered, slow-spread crust.

Many sites (or types of sites) in various tectonic and magmatic settings were discussed as potentially relevant to Mission Moho scientific objectives, including three listed below.

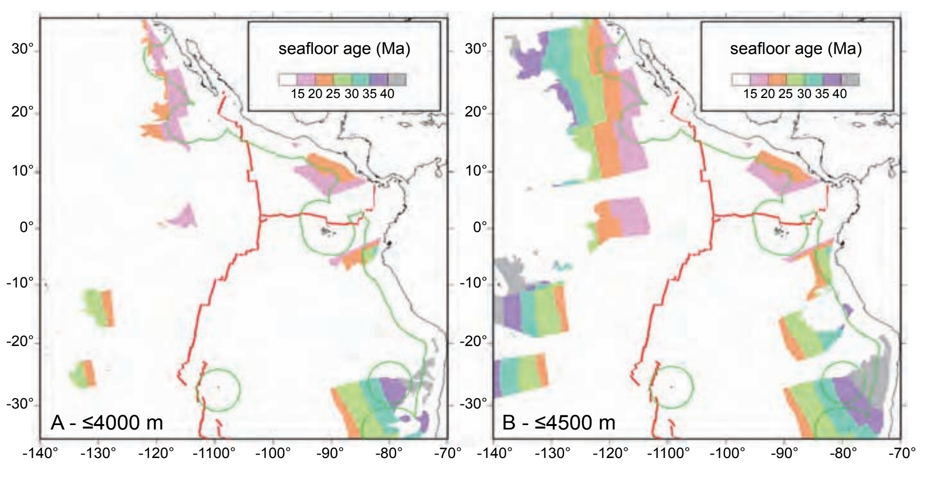

Figure 6. Areas accessible for deep riser drilling by *Chikyu* in the eastern Pacific, depending on the riser depth capability. Colored areas correspond to reasonably well-mapped and tectonically simple crust that is older than 15 Ma, and less than [A] 4000 meters or [B] 4500 meters below sea level. Green lines delimit the Exclusive Economic Zones of countries that are not IODP members (Figure by Doug Wilson).

A) Sites in magma-rich, volcanogenic portions of slow-spread crust (e.g., DSDP Site 332, Mid-Atlantic Ridge, 37°N 34°W; Lucky Strike segment, Mid-Atlantic Ridge, 37°20'N 32°-32°30'W) provide opportunities to compare and contrast magmatically robust parts of slow-spreading centers with fast-spreading ridges. ODP Site 332, ~1800 m below sea level, was drilled during DSDP Leg 37 and penetrated 310 m into basement. Drilling conditions and water depth at this site are suitable for relatively deep, non-riser drilling into the upper, basaltic crust. The Lucky Strike segment of the Mid-Atlantic ridge is well known, although it has not been surveyed specifically for drilling (e.g., Escartin et al., 2001; Singh et al., 2006). Lucky Strike is one of the main sites of the long-term monitoring of the Mid-Atlantic ridge (MoMAR) initiative, offering a potential opportunity to link a deep borehole with local seafloor observatories.

B) Sites in oceanic core complexes offer a large number of drilling options, including the opportunity to penetrate tectonically uplifted Moho. The two deepest holes in slow-spread ocean crust—and two of the four deepest holes in ocean crust—are ODP Hole 735B (1508 m deep; Dick et al., 1999, Fig. 2A) in Atlantis Bank (Southwest Indian Ridge, 33°S 57°E), and IODP Hole U1309D (1415 m deep; Blackman et al., 2006; Fig.2B) in Atlantis Massif (Mid-Atlantic Ridge, 30°N 42°W).
   - IODP Hole U1309D is open and in good condition, offering the opportunity to drill deeper at any time. Its apparent seafloor age is young (~2 Ma), likely too warm to allow drilling beyond 2–3 km. Nevertheless, continuing this hole as far as possible with current, non-riser technology will provide valuable operational experience, test drilling feasibility in relatively young gabbroic crust, and most certainly provide unique additional scientific return on lower crustal processes at slow-spread ridges. The operational experience is independent of spreading rate and will be directly relevant to fast-spread crust.
   - ODP Hole 735B is located in older (~11 Ma) crust, and could be a suitable place for deep drilling, and eventually testing the proposed models of slow-spread crustal architecture (Dick et al., 2007).
   - Three other potential sites that have site survey data available include Kane megamullion, Mid-Atlantic Ridge, 23°30'N 45°30'W; Godzilla megamullion, Parece-vela Basin, 16°N 139°E; and Uraniwa-Hills, Central Indian Ridge, 25°S 70°E.

C) A site in ultra-slow-spread crust (e.g., eastern Southwest Indian Ridge, 26–31°S 61–66°E; Gakkel Ridge; Arctic Ocean) could address objectives related to global-scale spatial variability of the crust. In addition, the abundance of mantle peridotites exposed along ultra-slow spreading centers suggests that a well-chosen site might achieve a long-standing elusive goal—to access fresh peridotite by relatively shallow drilling. In the Indian Ocean, "smooth" sea-floor areas interpreted as being the expression of the lowest magmatic activity (Cannat et al., 2006) are generally less than 4000 m deep and therefore accessible to future riser drilling by the *Chikyu*. The Gakkel ridge in the Arctic (e.g., Michael et al., 2003) offers similar settings, but its extreme northern latitude would require special (MSP) drilling arrangements.

Mission Moho: a Technological Challenge

Penetrating the entire ocean crust will require riser drilling technology. The world's only scientific riser drilling vessel *Chikyu* ("Earth" in Japanese) is scheduled to start operations for IODP in September 2007. For eventual penetration of fast-spread oceanic crust, a technically challenging modification of the riser will be required, from the current 2500-m maximum water depth to at least 4000 m (preferably 4500 m). The construction of such a deep-water riser was recently included as one of five domestic science and technology high priorities by the Japanese government.

Technological requirements for Mission Moho scientific objectives were discussed at the Mission Moho workshop by a special panel that included several drilling engineers. In addition to deep drilling, the panel considered improved core recovery, the ability to obtain oriented cores, and higher temperature tolerances (>150°C–200°C) for drilling, and especially logging tools. More experience is needed to drill in high temperature conditions, especially to understand the effects of thermal stress on hole stability in ocean crust lithologies. The temperature and cost limits beyond which we are unlikely to successfully drill are currently unknown. They will need to be established through the experience of drilling progressively deeper holes.

In planning for Mission Moho, the following broad guidelines should be considered:

- To achieve a Mission Moho requires a commitment to a ~10-year program of increasing complexity.
- Mission Moho will occupy about 4–6 sites, including at least one primary and one alternate site as well as several complementary sites. Most sites will require multiple expeditions—we estimate 12 to 20 expeditions in total.
- A riser capable of drilling in at least 4000 m water depth will be required for the second half of the 10-year mission.

If the riser can be engineered for 4500 m water depth, the range of possible sites is significantly increased (Fig. 6). Whether this is achievable must be known early in the mission to allow for final selection of a deep penetration site.

The journey to Moho will be long, but the challenges to our imagination and the potential for major scientific discoveries along the road are enormous. Each of the diverse recommended activities is essential to build a scientific and operational knowledge base that will ultimately enhance our ability to design and execute an ultra-deep drill hole that will penetrate all the way to the Earth's mantle.

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The Wunstorf Drilling Project: Coring a Global Stratigraphic Reference Section of the Oceanic Anoxic Event 2

by Jochen Erbacher, Jörg Mutterlose, Markus Wilmsen, Thomas Wonik, and the Wunstorf Drilling Scientific Party

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Introduction and Goals

The mid-Cretaceous greenhouse world (Albian–Turonian) was characterized by high atmospheric carbon dioxide levels, much higher global temperatures than at present, and a lack of permanent ice caps at the poles (Bice et al., 2006; Huber et al., 2002; Wilson et al., 2002). A characteristic feature of this greenhouse world was the deposition of black shales during the Cenomanian / Turonian boundary interval (CTBI; Schlanger and Jenkyns, 1976; Arthur et al., 1990). These carbon-rich sediments reflect a major perturbation of the global carbon cycle, with an associated global Ocean Anoxic Event (OAE 2). Despite twenty years of research, the OAE 2 still remains critical for the understanding of some of the mechanisms driving the climate and ocean systems during this period of extreme warmth. Numerous Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sites and many on-shore sections throughout the world have recovered sediments of CTBI age. However, many of these CTBI records and OAE 2 suffer from relatively poor stratigraphic control, which greatly reduces the options to correlate paleotemperatures and carbon isotope records to micro- and macropaleontological findings on a high-resolution scale.

In order to fill this gap, an onshore drilling project, funded by the Deutsche Forschungsgemeinschaft (DFG), has been initiated. In March 2006, an 80-m-long core, covering the CTBI, has been successfully recovered near Wunstorf (20 km east of Hannover, Germany, Fig. 1). The easily accessible Wunstorf section is a highly expanded, middle Cenomanian to early Turonian succession exposing a thick black shale sequence. The Wunstorf drilling site was placed next to a former quarry which supplied abundant and well preserved macro- and microfossils.

The Wunstorf drilling project aims at establishing a high resolution stable isotope record for the black shale succession (OAE 2) of the CTBI and developing this into a globally applicable high resolution bio- and chemostratigraphic reference section. Disciplines involved include micropaleontology (calcareous nannofossils, planktonic foraminifera), macropaleontology (ammonites, inoceramids), stable isotopes and cyclostratigraphy mainly based on borehole logging, multi sensor core logging, and x-ray fluorescence (XRF) scanning data. The combination of geochemical, paleontological, and logging data will allow high resolution chemo- and biostratigraphy for the CTBI which may in the future serve as an international standard.

The Wunstorf Core

In northwest Germany, the sediments of the CTBI are partly represented by finely laminated, total organic carbon (TOC) rich black shales deposited under dysoxic to anoxic conditions (at Wunstorf, Misburg, and Hesseltal) in shallow basins on a wide shelf at a paleolatitude of approximately 40°N (e.g., Ernst et al., 1984; Wilmsen, 2003). Out of these localities Wunstorf (Fig. 1) offers the most expanded black shale sequence and, micropaleontologically, the best suited lithology. Based on field studies and archive data, the drill site was chosen about 500 m west of the former quarry (Fig. 1).

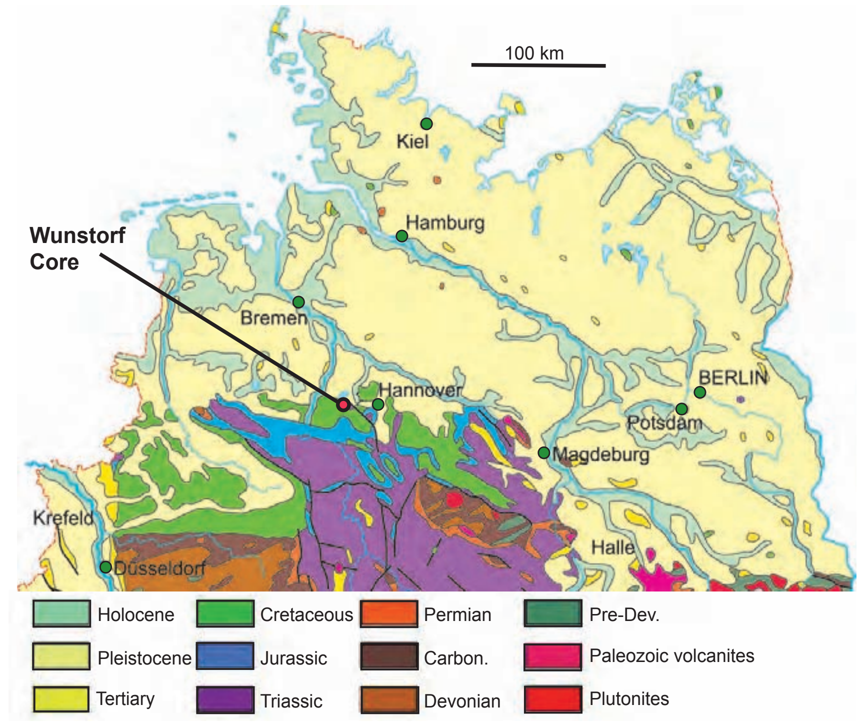

Figure 1. Geology of Northern Germany with location of the Wunstorf bore hole.

Figure 2. Coring at the Wunstorf drill site in March 2006.

The Wunstorf core was successfully drilled in early March 2006 by a truck-mounted mobile drilling system in a five-day campaign (Fig. 2). The 80-m-long core, which had excellent recovery (>98%), is now stored in the Bremen Core Repository (BCR). Subsequently downhole logging has been conducted with a broad variety of logging tools—including spectral gamma ray, density, neutron porosity, geochemical logging, sonic, borehole televiewer, resistivity, induced polarization, dipmeter, susceptibility, temperature, and salinity—and will be integrated with the core logging data.

Lithologically, the core consists from bottom to top of a) 30.5 m of middle and upper Cenomanian limestones (80–49.5 m), b) 26.5 m of upper Cenomanian and early Turonian alternating marls and black shales (49.5–23 m), and c) 18 m of lower Turonian marly limestones (23–5 m). The marl to black shale succession of interval b) covers the OAE 2 *sensu strictu*. The OAE 2 consists of sixteen dark TOC-rich beds up to 110 cm thick interbedded with pale and green marls (Fig. 3).

After the core was split into an archive and a working half, a detailed description of the whole core was made (Fig. 4). Subsequently, the core has been logged with the Multisensor Core Logger available at the BCR. After an initial sampling party in April 2006, the first studies of this core are currently underway, including stratigraphy and sedimentology (Würzburg, Berlin), stable isotope stratigraphy (Federal Institute for Geosciences and Natural Resources, BGR, Hannover; Bochum, Germany), inorganic geochemistry (University Oldenburg, Germany), organic geochemistry, x-ray fluorescence (XRF) spectroscopy scans, benthic and planktonic foraminifera (BGR Hannover, Germany), tetraether index (TEX86, Netherlands Institute for Sea Research, NIOZ, Texel, The Netherlands), dinoflagellates (Kingston, Frankfurt, Germany), and cyclicity (IfM GEOMAR, Leibniz Institute for Marine Geosciences, Kiel, Germany).

The analytical phase of the multi-disciplinary project is scheduled for the next two years. Samples will be prepared according to the disciplines involved. Following compilation of data by each group/discipline, a synthesis study is planned for the final phase of the project.

First Data

The core description and the gamma-ray data from downhole logging revealed eight to nine short-termed, potential eccentricity cycles (100 ky) for the 26.5-m-thick OAE 2 black shale succession, giving a duration of 850 ky for this interval with a mean sedimentation rate of ~31 m My^{-1}.

Figure 3. Meters 44 to 38 of the Wunstorf core showing dark laminated black shales.

Wunstorf Coring Scientific Drilling Party

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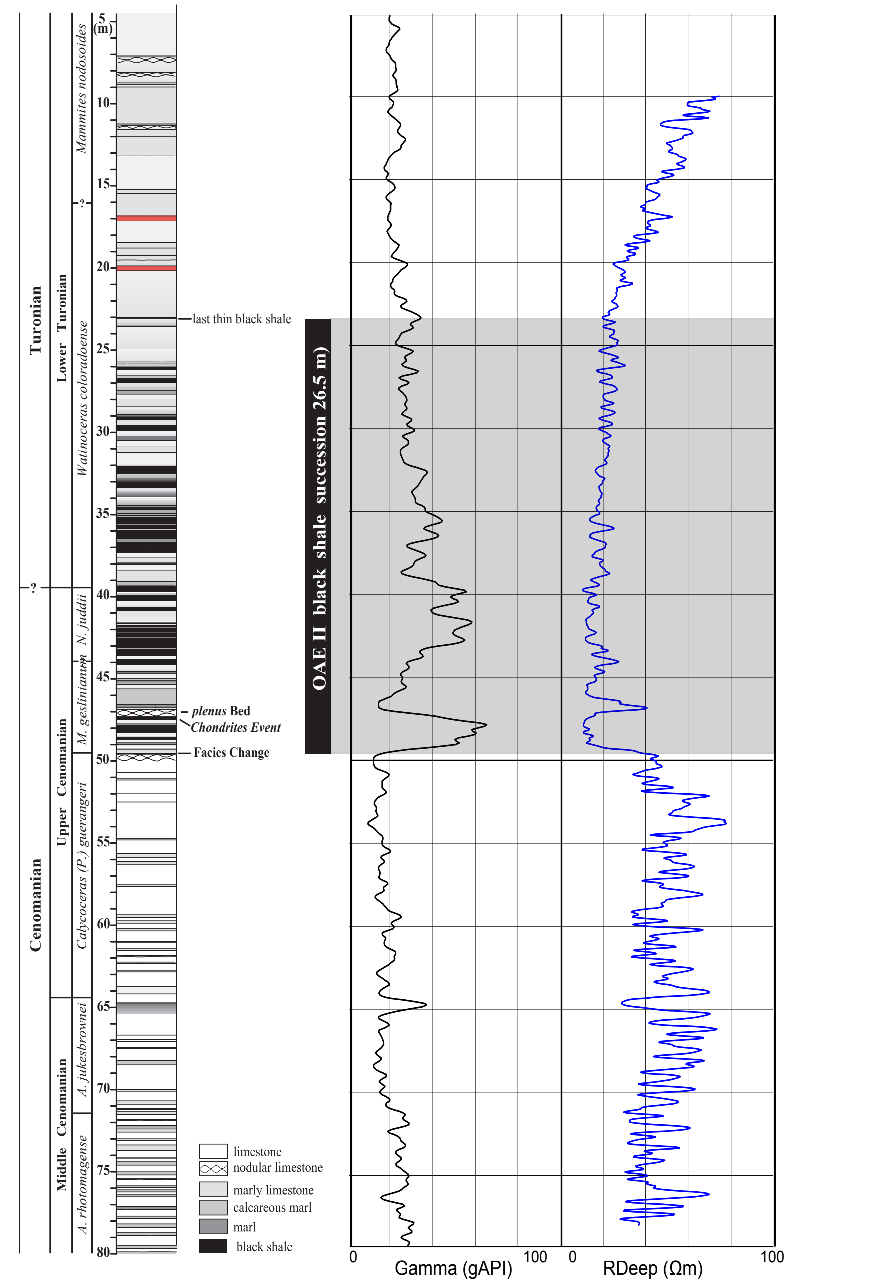

Figure 4. Schematic litholog of the Middle Cenomanian–Lower Turonian of the Wunstorf Core, plus γ-ray and resistivity downhole logs. Columns in litholog from left to right show stages, substages, ammonite biozones, depth in meters below surface, lithology, and prominent lithostratigraphic intervals.

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Fig. 2. Photo by J. Erbacher
Fig. 3. Photo by I. Jarvis

Rhizon Sampling of Pore Waters on Scientific Drilling Expeditions: An Example from the IODP Expedition 302, Arctic Coring Expedition (ACEX)

by Gerald R. Dickens, Martin Koelling, David C. Smith, Luzie Schnieders, and the IODP Expedition 302 Scientists

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Introduction

For more than 35 years, interstitial water (IW) samples have been collected from sediment recovered during marine scientific coring expeditions. Pioneering work of DSDP and ODP quickly demonstrated that pore water chemistry differed from that of overlying seawater and from one location to another for myriad reasons (Sayles and Manheim, 1975). Extraction and analysis of IW samples has now become routine on deep-sea drilling cruises; the ensuing pore water profiles are being used to understand a range of processes, such as subsurface fluid flow (e.g., Brown et al., 2001; Saffer and Screaton, 2003), mineral diagenesis (e.g., Rudnicki et al., 2001; Malone et al., 2002), microbial reactions (e.g., Böttcher and Khim, 2004; D'Hondt et al., 2004), gas hydrate dissociation (e.g., Egeberg and Dickens, 1999; Tréhu et al., 2004), and glacial to interglacial changes in the composition of bottom water (e.g., Paul et al., 2001; Adkins and McIntyre, 2002).

The procedure for obtaining IW samples has continued relatively unchanged since early DSDP expeditions (Manheim and Sayles, 1974; Gieskes et al., 1991). Immediately after recovery, a short length of sediment (typically 5–15 cm long) is cut from a core along with its surrounding liner. This "whole-round" interval is taken to a laboratory, where the sediment plug is extruded from the liner, scraped to remove contamination, and placed inside a squeezer, where pressure is applied with a hydraulic press. Emerging waters are filtered, collected, and dispensed into aliquots for analyses.

Geochemists and microbiologists increasingly desire "high-resolution" pore water profiles, especially within 50–100 m of the seafloor (e.g., Egeberg and Dickens, 1999; Paul et al., 2001; Adkins and McIntyre, 2002; D'Hondt et al., 2004), and this often necessitates IW samples spaced every 2 m or less. Such whole-round squeezing comes with two major problems. First, it demands considerable labor and time, and secondly and most critically, the removal of whole-rounds destroys the sedimentary record. High-resolution IW sampling, although desirable, will not happen at most sites unless non-destructive techniques are developed to collect numerous good samples with minimal effort.

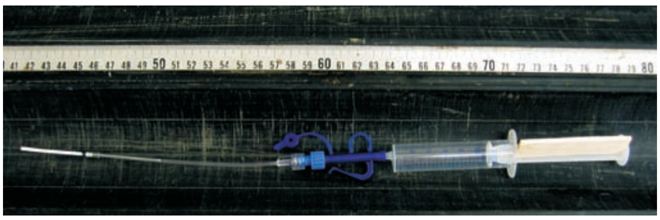

Figure 1. A Rhizon MOM 5-cm soil sampler with tube connector and syringe propped open with a wooden spacer

Rhizon samplers (discussed below) are thin tubes of hydrophilic porous polymer designed to extract water from porous sediment using a vacuum. Unlike the aforementioned squeezing or some other common IW collection methods (e.g., centrifuging, pressurized gas) that "push" water from discrete sediment samples, Rhizon samplers "pull" water from intact sediment, thereby preserving the sedimentary record. They are also inexpensive and disposable, which eliminates the intensive cleaning steps associated with squeezers. Several studies have used Rhizon samplers to obtain waters from terrestrial soils (e.g., Knight et al., 1998; Tye et al., 2003). Recently, they have been successfully used to obtain pore waters from marine sediment collected in a gravity core or below a benthic chamber (Seeberg-Elverfeldt et al., 2005). Here, we evaluate and discuss the first use of Rhizon samplers on drill cores. The chosen cruise, Expedition 302 of the Integrated Ocean Drilling Program (IODP), is significant because its paleoceanographic objectives precluded collection of numerous IW samples by conventional methods.

Pore Water Problem and Rhizon Solution

IODP Expedition 302 was designed to reconstruct the Cenozoic oceanographic history of the central Arctic Ocean (Backman et al., 2006) One specific aim within this broad goal was an understanding of the sedimentary manganese record in the first 10–50 m below seafloor (mbsf). Piston cores from the central Arctic Ocean show a series of solid-phase manganese spikes, which may record past changes in bottom water redox conditions (Li et al., 1969; Jakobsson et al., 2000).

A full appreciation of sedimentary manganese spikes requires complementary dissolved Mn^{2+} profiles (e.g., Burdige and Gieskes, 1983; Wallace et al., 1988), however, the requisite pore water sampling to generate such a profile presented a challenge for Expedition 302. Preservation of continuous core was desired to address first priority expedition objectives. Construction of an appropriately detailed dissolved Mn^{2+} profile in shallow sediment was therefore incompatible with Expedition 302 operations using traditional means for collecting IW samples.

Rhizon samplers present an unconventional method to collect IW samples from drill cores. In general, a Rhizon sampler consists of four parts (Seeberg-Elverfeldt et al., 2005): (1) a thin tube comprised of hydrophilic polymer, (2) a wire to support the tube, (3) a flexible hose to pass water from the tube, and (4) a connector. The porous tube is inserted into the sediment, and an evacuated container is attached to the connector. Pore water then passes from sediment through the porous tube and flexible hose into the collection chamber. Given a sufficiently small tube pore size (0.1 µm), the Rhizon sampler also serves as a filter, removing microbial and colloidal contamination (Knight et al., 1998).

For Expedition 302, we selected Rhizon MOM 5 cm soil samplers (Fig. 1). These have an outer diameter of 2.4 mm, a length of 5 cm, a minimum pore size of 0.1 µm, a nylon supporting wire, and a PVC hose with a female luer-lock connector. They were the same as those used by Seeberg-Elverfeldt et al. (2005).

Rhizon samplers collect interstitial water most efficiently when their pores are saturated with water prior to insertion. For Expedition 302, porous tubes were submerged in a beaker of deionized water for at least 30 minutes before use. Each Rhizon nominally contained 0.5 mL of deionized water before IW sampling.

Site and Sample Collection

IODP Expedition 302 drilled five holes at four sites on the Lomonosov Ridge at ~88.5°N latitude, 136–140°E longitude, and in 1206–1288 m water depth (Backman et al., 2006). The five holes (M0002A, M0003A, and M0004A–C) have been grouped together as a single drill site because they are proximal, and because seismic reflection profiles show the same basic stratigraphy at each hole (Backman et al., 2006). Collectively, cores (~4.5 m in length) recovered at this site span a 428-m-thick Campanian to Recent sedimentary sequence with several hiatuses. In this paper, we restrict discussion to the upper 50 mbsf because this is where we employed the Rhizon samplers. Sediment in this interval comprises soft, silty clay of Latest Pliocene to Recent age (Backman et al., 2006).

Cores were passed down a Geotek logger immediately after recovery to establish basic physical properties (sonic velocity, magnetic susceptibility, gamma attenuation and resistivity). Once initially logged, IW samples were obtained by two methods: (1) cutting of whole-round intervals and squeezing, and (2) Rhizon sampling of intact cores. Cores were logged again after several hours.

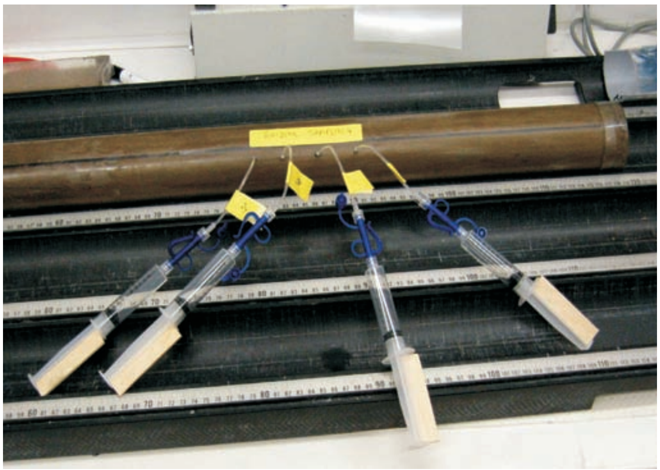

Figure 2. Four Rhizon samplers collecting water under vacuum from a ~10-cm interval of a shallow core.

Whole-round intervals of approximately 5–10 cm length were taken every third or fourth core. The overall procedure (Backman et al., 2006) was similar to standard IODP protocol, with one notable exception. Because samples were taken after logging, there was a 30 to 40 minute delay in processing. However, this time lag probably did not modify pore water chemistry (at least relative to IW collection on previous expeditions) because temperatures of the shallow water column and ship deck were very low (<5°C). In total, seven IW samples were taken over the upper 50 mbsf, similar to the resolution on many deep-sea coring expeditions.

While cores equilibrated for re-logging, intervals were selected on the designated working half of core sections for Rhizon sampling. For these intervals, between one and four 5-mm-diameter holes were drilled through the core liner 1–2.5 cm apart (Fig. 2). The number and distances were adjusted to assess the minimum number of samplers required and "effective sampling distance". Saturated Rhizon samplers were wiped clean to remove excess water, and inserted through the holes so the porous tube was just buried. A tube connector with double luer-locks was connected to each Rhizon sampler, and then a 10-mL syringe was attached to each tube connector, pulled to generate a vacuum, and held open with a spacer (Seeberg-Elverfeldt et al., 2005). Cores were then turned so that water along the inside of core was at the bottom and away from the Rhizon samplers. The initial 1-mL in each syringe was discarded, while the rest was retained. In cases where Rhizons were taken <10 cm apart, water samples were pooled to make one IW sample. In total, thirty-nine Rhizon IW samples were taken over the upper 50 meters drilled.

After collection of IW samples, aliquots were taken for various chemical analyses, depending on the total amount of water. The methodology and results of these analyses are presented by Backman et al. (2006), although we briefly note the analytical technique for the two sets of measurements presented here. Dissolved ammonium (NH_4^+) was determined on 0.5-mL aliquots at sea using the "Teflon tape gas separator method" (Hall and Aller, 1992); dissolved Mn^{2+}

was determined on dilutions of 5-mL aliquots treated with ultra-pure concentrated HNO_3 in the Department of Geosciences, University of Bremen, using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

Results and Discussion

Repeated tests showed that deionized water flows through Rhizons at >10 mL h^{-1}. This rate slowed considerably to 0.3–3.0 mL hr^{-1} when Rhizons were placed into sediment. Moreover, there was a quasi-exponential decay in flow with core depth (Fig. 3), which probably relates to physical properties (e.g., decreasing porosity and permeability). Water did not flow appreciably from cores at >50 mbsf; however, Rhizon samples from <50 mbsf rendered IW samples of sufficient volume for chemical analyses. This was especially true after adjacent Rhizon samples were pooled. In most cases, at least 10 mL of pore fluid could be collected from four adjacent Rhizon samplers within 5 hours. It was interesting to note that multiple Rhizons did not appear to impede water flow over this time interval unless spaced about 1 cm apart. This is consistent with tests and modeling results conducted by Seeberg-Elverfeldt et al. (2005).

Water obtained from Rhizons had a similar chemistry to that obtained from conventional squeezing over the upper 25 mbsf (and perhaps 50 mbsf), considering experimental caveats. This was true for all dissolved species examined, but highlighted here for NH_4^+ and Mn^{2+} (Fig. 3). However, the time and energy expended to collect all thirty-nine Rhizon samples were much less than that for the seven squeezed samples.

Diffusion should dominate pore fluid profiles on Lomonosov Ridge, given the absence of significant tectonic compression and the generally low compaction rates (Backman et al., 2006). Consequently, smooth pore water

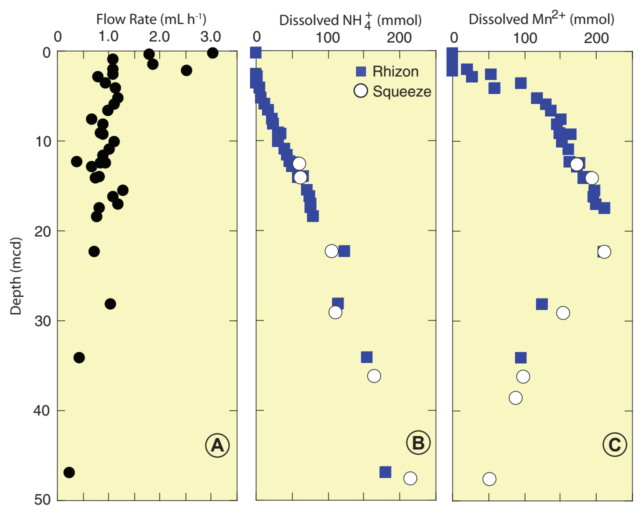

Figure 3. Downcore profiles of water sampling and analyses for the upper 50 m below seafloor on IODP Leg 302. [A] Fluid flow rate into Rhizon samplers averaged across examined sediment intervals. [B] Dissolved ammonium. [C] Dissolved manganese.

concentration profiles should be expected, except across zones of chemical reaction (D'Hondt et al., 2004). This is true for all species analyzed using Rhizon samples on IODP Expedition 302, especially after adjusting core depths between the five holes from mbsf to mcd (meters composite depth; Backman et al., 2006). For NH_4^+ and Mn^{2+}, the constructed depth profiles displayed smooth trends in concentration and clear changes in concentration gradients, notably the concave-up inflections between 3 and 5 mcd (Fig. 3). These are most likely short depth intervals where NH_4^+ and Mn^{2+} are consumed, probably via microbial reactions. These inflections would have been missed with conventional pore water collection because of sampling resolution.

Cores recovered from adjacent deep-sea holes often display lithological and physical property changes offset in terms of recorded depth below the seafloor, presumably because of imperfect coring and differential core expansion (e.g., Hagelberg et al., 1995). Some of the offset in the Rhizon generated pore water profiles on Expedition 302 (Fig. 3) may reflect subtle misalignments of physical property measurements among the five holes. It is conceivable that, in regions where pore waters display obvious diffusion gradients, sediment cores from adjacent holes could be aligned, beyond physical property measurements, by using high-resolution pore water profiles obtained by Rhizons.

Other than the shallow depth restriction, there appears to be only one minor problem with Rhizon sampling of deep-sea sediment cores. After Rhizons are inserted, some intervals showed a slight drop in P-wave velocity of sediment. The simplest explanation is that extraction of water from the sediment causes the core to shrink, leaving air space between the sediment and the core liner.

Acknowlegements

We sincerely thank the captains and crews of the three ice-breaking ships (*Oden*, *Vidar Viking*, and *Sovetskiy Soyuz*) involved in the ACEX cruise, along with the ice management and drilling teams. Without the collective efforts of these people, we would still lack drill cores from the central Arctic Ocean, let alone a test of Rhizon samplers. We also thank the co-chief scientists Jan Backman and Kate Moran, who enthusiastically gave us permission to test Rhizon samplers in precious cores.

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Progress Report on the Iceland Deep Drilling Project (IDDP)

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Introduction

The Iceland Deep Drilling Project (IDDP) is a project of "Deep Vision", a consortium of the government and the three leading energy companies in Iceland. It aims to improve the economics of geothermal energy production by exploring for supercritical hydrothermal fluids as a possible energy source. This will require drilling to depths of 4 to 5 km in order to reach temperatures of 400°C–600°C. From the outset, Deep Vision, recognizing that a broad scale of studies would be necessary in order to explore the little understood supercritical environment, welcomed the inclusion of basic scientific studies in the IDDP and invited participation from the international scientific community, to the mutual advantage of both industrial and scientific participants (Fridleifsson and Albertsson, 2000). The guiding principle was that the incremental costs of drilling and sampling for the science program, and their subsequent study, should be provided by the scientific community. Two planning workshops funded by the International Continental Scientific Drilling Program (ICDP) were held in 2002, and a two-year-long feasibility study funded by Deep Vision was concluded in 2003 (Fridleifsson et al., 2003). Modeling indicates that if well-head enthalpy is to exceed that of conventionally produced geothermal steam, the reservoir temperature must exceed 450°C. Producing high-enthalpy steam from a well penetrating a reservoir >450°C at a rate of 0.67 m^3s^{-1} would be enough to generate 40–50 MW of electricity. This is an order of magnitude greater than the power produced by existing geothermal wells in Iceland. Three high-temperature geothermal fields, at Reykjanes, Hengill, and Krafla, were selected as sites for deep drilling (Fig. 1). In late 2003 a member of the consortium offered one of its planned exploratory wells located on the Reykjanes peninsula for deepening by the IDDP (Fridleifsson and Elders, 2005). It was completed at 3.1 km depth in February 2005; however, this well of opportunity became blocked during a flow test in November 2005. After subsequent attempts at reconditioning failed, it was decided in February 2006 to abandon the hole, requiring a change in the IDDP work plan.

In June 2006, after careful consideration of all of the options available, Deep Vision decided to move operations to Krafla, the northernmost of the high-temperature areas (Fig. 1) as the site for the first deep IDDP borehole. This location is within a volcanic caldera with higher temperature gradients and more recent volcanic activity than Reykjanes (Fig. 2). The IDDP plan is to rotary drill and spot core this hole to 3.5 km depth and subsequently deepen it to 4–5 km using continuous wireline coring for scientific purposes, and then attempt a flow test from the deepest portion of the well. This plan is a compromise between the desire to obtain as much drill core as possible and technical and budgetary limitations.

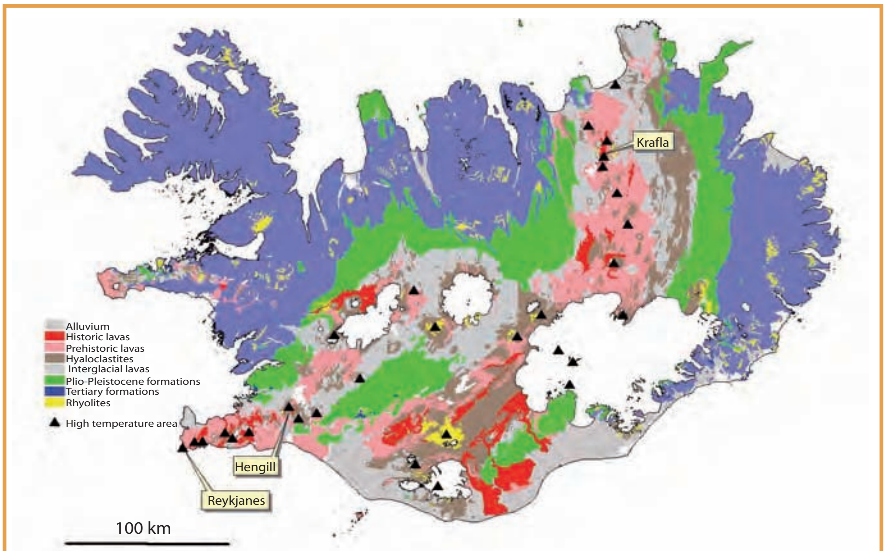

Figure 1. A geological map of Iceland showing the location of the three high-temperature hydrothermal systems being considered as sites for deep boreholes by the IDDP. (Map compiled by Haukur Johannesson and Kristján Saemundsson, ISOR)

Need for Coring

The study of the coupling of the chemical and mineral alteration, fracture propagation, pressure solution, and fluid flow will be based on analysis of data on mineral chemistry, isotopes, geothermometry, and fracture geometry. Without drill cores, it is impossible to unravel the nature and chronology of fracture failure and vein infilling, to detect time serial fracture events, to determine constitutive rock properties, and to understand the nature and formation of permeability. Measurements of mechanical and thermal properties of core as a function of temperature are necessary to quantify processes related to brittle-ductile behavior. The permeability and thermal diffusivity of fractured and intact,

Figure 2. A view to the Krafla Central Volcano. A 60 MW power plant is seen in the foreground. The red circle denotes the potential IDDP drill site (Photo by Emil Thor, Iceland).

fresh and altered, basalt comprise essential baseline information for fluid circulation models. There are also practical reasons for coring. Lost circulation during drilling, which is common in highly permeable zones in Iceland, would prevent recovery of drill cuttings. Similarly, the use of borehole televiewers and most other logging tools is impossible because of high temperatures. Recognizing when the supercritical conditions are reached during drilling will best be done by studying mineral assemblages and fluid inclusions in cores as they are recovered. However, because continuous coring is slower and therefore more expensive than conventional drilling, it was decided to reserve continuous coring for the supercritical zone and to take only spot cores in the upper part of the well. In the event of total loss of circulation, it may be possible to use special downhole logging tools rated up to 300°C, by sufficient cooling of the well down to the feed point. However, when downhole logging is not possible and there is loss of circulation and no return of drill cuttings in the supercritical zone, the only alternative is to obtain drill cores from these zones of greatest interest.

In addition to exploring for new sources of energy, the IDDP project will provide the first opportunity worldwide for scientists to investigate the deep, high temperature reaction zone of a mid-ocean ridge hydrothermal system that reaches supercritical conditions, with amphibolite facies grade of metamorphism (>400°C). The drill site is ideally situated for a broad array of scientific studies involving water/rock reactions at extremely high temperatures in active setting. Active processes in such deep high-temperature reaction zones that control fluid compositions have never before been available for comprehensive direct study and sampling.

In autumn 2006 tenders were solicited for casings and valves for the proposed well, as well as pre-qualification documents for drilling contractors. Given the competitive market situation for drilling rigs, and associated year-long lead times in obtaining well completion materials, we anticipate that drilling will not start before spring 2008. It should take about four months to reach 3.5 km depth, including about two weeks for spot coring. Deep Vision will pay for drilling and completing the well, but the spot coring will be funded by ICDP and the U.S. National Science Foundation (NSF). Deepening the well to about 4.5 km depth will take an additional two to three months with continuous wireline coring, with the incremental costs of coring being substantially funded by ICDP and NSF. The drilling went out for international bidding in December 2006, and a contract is expected to be signed in early 2007 for drilling and casing the well to 3500 m in 2008. Depending on logistics and progress within the first phase, the continuous coring phase may have to be deferred to 2009.

Predicting P-T Conditions in the Krafla Well

The features of paramount importance related to the drilling of the IDDP well are (1) the presence, size, and specific location of a magma chamber previously interpreted to exist

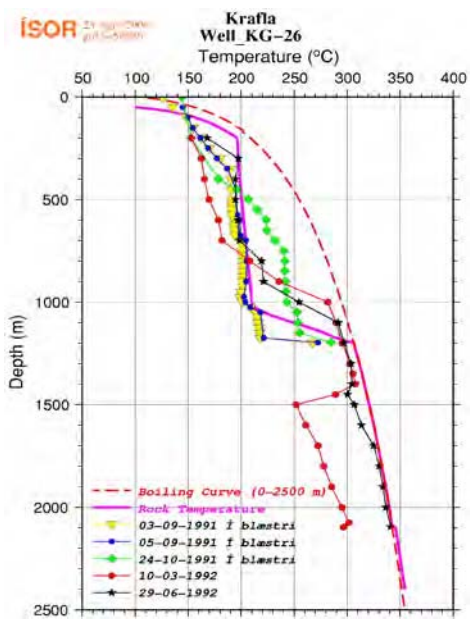

Figure 3. Temperature profiles during ("í blæstri") and after flow tests in well KG-26 in 1991 and 1992. Because of low permeability, since 2002 well KG-26 has been used as a re-injection well. Based on the calculation of the formation temperature, the pre-drilling temperature at 2400 m would have been 354°C.

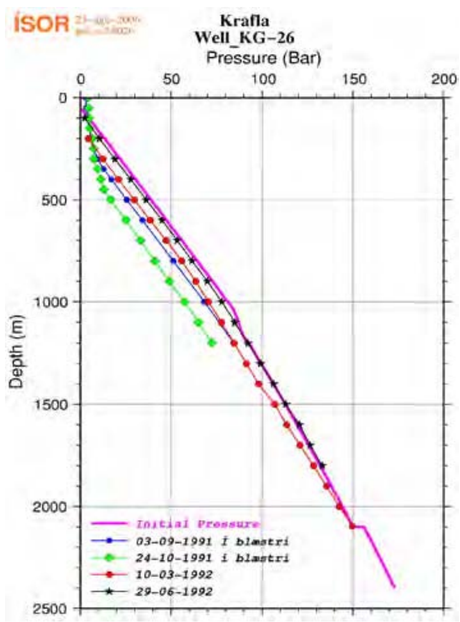

Figure 4. Pressure curves corresponding to the temperature logs in well KG-26. The initial pressure curve corresponds to the initial pressure within the formation.

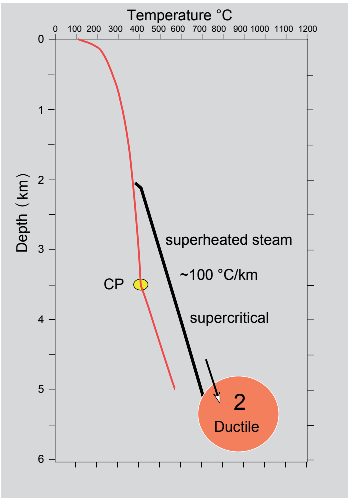

Figure 5. A temperature scenario for a drill hole penetrating a contact aureole along the vertical margin of a cooling intrusion, involving upward flow of superheated steam derived from supercritical fluid.

beneath the Krafla caldera, (2) the pressure-temperature conditions within the geothermal field, and (3) the nature of permeability at depth at the drill site. The magma chamber in Krafla was inferred from S-wave attenuation during the volcanic eruptions at Krafla in 1975–1984, and it was interpreted to be at 4–8 km depth below the drill field (Einarsson 1978; Björnsson, 1985). The current thermal conditions within this body are not known. One of the aims of the IDDP at Krafla is to drill into the seismogenic zone at 4–5 km depth to determine if the formation of natural fractures at high temperatures generates permeability and to test the hypothesis that the base of the upper crustal seismogenic zone marks the transition from brittle to ductile behavior.

At Krafla plans are underway to expand production from 60 MW to 100 MW electricity. A recent report on the geothermal conditions at Krafla is available at the IDDP website (http://www.iddp.is), and this report is partly based on earlier reports on Krafla (Ármannsson et al., 1987, 1993; Björnsson and Steingrímsson, 1991; Gudmundsson, 2001). Well KG-26 is at about 300 m distance from the site selected for the IDDP well, and we expect P-T conditions to be similar. Figures 3 and 4 show temperature (T) and pressure (P) profiles from Well KG-26. These data show that conditions should follow the boiling-point-with-depth curve (BPD-curve) in the IDDP well from 1100 m depth downwards. For pure water the critical point would be reached at about 3.5 km depth, but for the geothermal fluids at Krafla (which have a TDS of 1000–2000 mg kg^{-1}) it could be somewhat deeper. The plan is to cement the third and last intermediate casing to ~3.5 km depth in the first phase of the IDDP well. Thus, supercritical conditions should be reached soon after drilling out of the 3.5 km deep casing. However, the possibility of reaching temperature conditions higher than that controlled by the BPD-curve at shallower depth also needs to be considered. For instance, the temperatures below 2200 m depth in Well NJ-11 at Nesjavellir in 1985 (Steingrímsson, et al., 1990) certainly surpassed the conditions determined by the BPD-curve and involved at least superheated steam hotter than >380°C. Therefore, during drilling of the IDDP well at Krafla, we also need be prepared for P-T conditions surpassing the BPD-curve. One such scenario is shown in Figure 5 (from Fridleifsson et al., 2003).

Site Location

The proposed location of the IDDP drill hole is close to the inferred southern margin of the magma chamber at 4–8 km depth. This site was selected in order *not* to intersect the hot magma body directly, where permeability could be absent, but rather to contact the permeable fluid heat exchange system at depth that surrounds it. We expect the P-T conditions would follow a path similar to that outlined in Fig. 6a. If, on the other hand, the IDDP borehole is too close to a cooling magma chamber, it could bottom in dry and ductile rock, a scenario shown in Figure 6b. This was the case in the 3.7-km-deep exploratory borehole at Kakkonda, in the Hachimanti Geothermal Field, Iwate Prefecture, Japan (Muraoka et al., 1998). That borehole penetrated into a neo-granitic pluton (tonalite with a K-Ar age of 0.19 Ma), a cooling granitic intrusion that is the heat source for the hydrothermal system. The shallow hydrothermal system exhibited a BPD-curve controlled temperature profile down to 3100 m depth, where a 380°C temperature was recorded and a transition from brittle to ductile conditions was observed. Temperatures reached >500°C at 3729 m (Muraoka et al., 1998). At the bottom of the borehole the permeability was very low and the borehole was subject to plastic deformation. For this reason the Kakkonda borehole was completed as a production well in the shallow hydrothermal system.

The design of the IDDP drill hole should be capable of handling both conditions outlined in Figures 5 and 6. For the well to be economically successful, in addition to reaching supercritical P-T conditions, good permeability is also necessary. Permeable structures, like major fractures channeling fluids from deeper heating zones, are needed. According to the IDDP feasibility report and references therein, such structures should exist within the Krafla geothermal field at depth. The drill site chosen was selected to optimize inter-

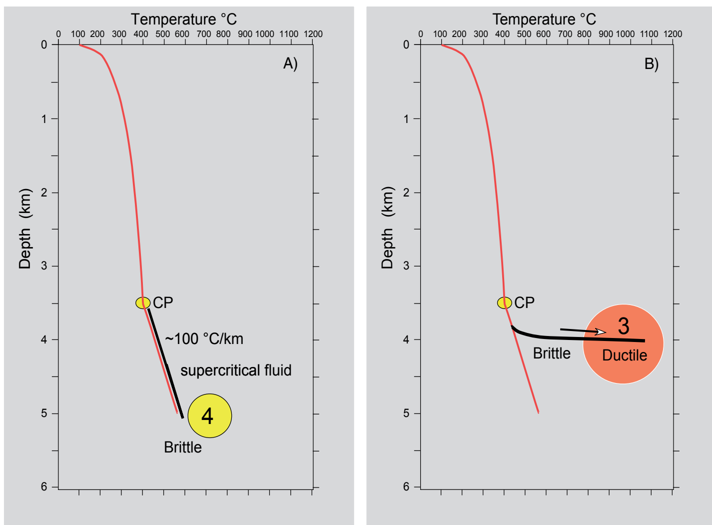

Figure 6. Two temperature scenarios for drill holes around a cooling intrusion at Krafla: [A] along the margin and [B] into a cooling magma body at ~4 km depth.

cepting potential fractures at depths. If the drill hole intercepts a major permeable fracture at shallower depth (e.g., between 2.4 and 3.5 km) that produces superheated steam—possibly at 500°C—derived from supercritical fluid at greater depths, efforts will be made to study it thoroughly before casing it off.

Expected Lithologies, Hydrothermal Alteration and Fluid Chemistry

Assuming that conditions will be similar to those found in Well KG-26, the expected hydrothermal conditions in the first 2500 meters of IDDP drill hole, there should be an upper system characterized by an isothermal fluid system at 200°C at about 200–1100 m depth, and a lower system following the BPD-curve between 1100 and 2500 m depth. These systems will be separated in the borehole behind cemented casings. The uppermost kilometer of the Well KG-26 penetrated two major hyaloclastite units separated by lava succession. Below 1 km depth a dense intrusive rock complex is expected, including felsic intrusive rocks at close to 2 km depth. Some of the intrusive rock contacts could involve reasonable sized feed points. If P-T conditions are similar to those in well KG-26, and if feed points occur at about 2.4 km depth, temperatures of >350°C and static pressure of about 180 bar can be expected at 2.5 km depth. Predicting the likely situation below 2.5 km depth is more difficult, and two different scenarios are envisaged. The most likely situation would be that P-T conditions follow the BPD-curve to about 3.5 km depth. On the other hand, if there is good vertical permeability, superheated steam could flow readily between depths of 2.5 and 3.5 km.

The fluids in the Krafla system are dilute (TDS 1000–2000 mg kg^{-1}), similar to those at Nesjavellir (TDS 1000–2000 mg kg^{-1}), whereas in Reykjanes salinity is close to that of seawater (TDS 30,000–35,000 mg kg^{-1}). The present Krafla fluid is in all respects good for production and is not likely to cause problems. During the eruptions of 1975–84, the CO_2/H_2S ratios in some geothermal wells at Krafla had a high magmatic component; however, gas compositions have returned to values similar to those obtained before the Krafla eruptions, including the values found for the upper and lower parts of KG-26. Exactly what the fluid composition will be like below 2.4 km depth in Krafla remains to be observed—an integral part of the IDDP project.

Acknowledgements

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Related Web Link

http://www.iddp.is

The Scientific Drilling Database (SDDB)—Data from Deep Earth Monitoring and Sounding

by Jens Klump and Ronald Conze

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Introduction

Projects in the International Scientific Continental Drilling Program (ICDP) produce large amounts of data. Since the start of ICDP, data sharing has played an important part in ICDP projects, and the ICDP Operational Support Group, which provides the infrastructure for data capturing for many ICDP projects, has facilitated dissemination of data within project groups. However, unless published in journal papers or books the data themselves in most cases were not available outside of the respective projects (see Conze et al. 2007, p. 32 this issue). With the online Scientific Drilling Database (SDDB; http://www.scientificdrilling.org), ICDP and GeoForschungsZentrum Potsdam (GFZ), Germany created a platform for the public dissemination of drilling data.

Access to Monitoring and Sampling Data

Effectively publishing data requires that data are citeable and that the location of the referenced data is unique and retrievable in the long term. In the past, the internet was a problematic reference for data because URLs are short-lived; therefore, data publication on the internet needs a system of unique and persistent pointers to a citeable web publication (Lawrence et al., 2001; Klump et al., 2006). For their conventional publications many scientific publishers use Digital Object Identifiers (DOI) for web referencing. GFZ is a member of the project "Publication and Citation of Scientific and Technical Data" using DOI techniques (STD-DOI). In this project the German National Library for Science and Technology (TIB Hannover), together with GFZ, the Alfred Wegener Institute (AWI) in Bremerhaven, the University of Bremen, and the Max Planck Institute for Meteorology in Hamburg, set up a system to assign DOIs to data publications (Brase, 2004; Paskin, 2005). Since May 2006 TIB Hannover is the first DOI registration agency for scientific and technical data worldwide, and GFZ Potsdam is one of its publication agents. To emphasize that the uploaded data have become citeable publications, SDDB displays bibliographical citation data with every dataset and offers an automated export of the citation data into common bibliographical database software (e.g., "Endnote", Fig. 1).

To make the exchange of data between databases easier, the database structure of SDDB is similar to the structure of the PANGAEA® database (Diepenbroek et al., 2002) and to the Drilling Information System used in ICDP projects and on IODP mission specific platform expeditions (Conze et al., 2007).

Access to data in scientific databases is commonly through some kind of search interface, which may consist of a simple field for the entry of keywords or may offer more elaborate search criteria. However, users rarely know the precise contents of a database, and yet few, if any, databases will offer datasets matching any search query. Database users therefore "browse" the contents. The design of the SDDB meets this challenge with its graphical user interface that contains dynamically generated catalogue listings and cross-links (e.g., between datasets and sample material, datasets and authors, datasets and parameters). The geographical and geological context of data is visualized in order to help the user to assess if the data are useful. At present visualization primarily shows the sampling positions in their geographical context. Virtual globes, such as Google Earth, are useful and intuitive tools for geographical visualization (Butler, 2006). To show the sampling locations, SDDB offers a file in Google Earth's kml format for download. The kml-file can be automatically imported as "place marks" and viewed in Google Earth (Fig. 2). The "place marks" are interactive and act as links back to the SDDB. In a second step, it is planned to add more specific maps which will be displayed alongside the data or as separate maps in an online geographical information system.

Figure 1. Screenshot of a data citation in SDDB. Note the buttons for download of citation into a reference manager and for the visualization of sampling locations in Google Earth. The Digital Object Identifier of this dataset is doi:10.1594/GFZ.SDDB.1043

Figure 2. Sampling locations of doi:10.1594/GFZ.SDDB.1043 by Heim et al., 2005. displayed in the Google Earth virtual globe. The place marks at the sampling locations link back to an online description of the field activities at the respective locations as recorded in SDDB.

The Data Upload Assistant

The effort that goes into preparing data for publication has deterred many potential data contributors from sharing their data through scientific databases. The data upload process by the SDDB data upload assistant, a browser-based user interface, must therefore be as simple as possible. The upload process is divided into four steps. In the first step, all necessary metadata are collected that will be required in the course of the upload process. In the second step, the title of the dataset, a short description, selects the number of authors and the data file for upload. If the data are organized as a table, the author selects the principal investigator for each data column in the third step, followed by the parameter measured, the type of sample material, and the method used for this measurement. In the fourth and final step, the author selects the license (i.e. restricted, open access, creative commons) and copyrights under which the data are to be published and the publication date.

Future Developments

The development of the SDDB is ongoing. The focus in the near-term will be on further improving the data upload process, drawing from the experience gained so far. The development of the user interface will also be guided by feedback from the scientific community. In addition, the SDDB will be equipped with interfaces to exchange data and metadata with other scientific information portals, such as IODP's Scientific Earth Drilling Information System (SEDIS; http://sedis.iodp.org), the World Data Center (WDC) MARE/PANGAEA (http://www.wdc-mare.org/), the Sediment Geochemistry Database SedDB (http://www.seddb.org), the petrological database of the ocean floor PetDB (http://www.petdb.org), the stratigraphic database CHRONOS (http://www.chronos.org), and others, as well as to provide a metadata harvesting interface that follows Open Archives Initiative standards (see www.openarchives.org).

In the longer term, the goal is to develop a close integration of geological sample information, the data derived from measurements on these samples, and the published studies in which the data are interpreted.

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Related Web Links

http://www.scientificdrilling.org
http://www.std-doi.de
http://sedis.iodp.org
http://www.wdc-mare.org
http://www.seddb.org
http://www.petdb.org
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Joint Data Management on ICDP Projects and IODP Mission Specific Platform Expeditions

by Ronald Conze, Hans-Joachim Wallrabe-Adams, Colin Graham, and Frank Krysiak

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Introduction

Data management in the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP) supports two functions: firstly, the capture of drilling and scientific data and secondly, the long-term storage and dissemination of these data. The data capture in both ICDP projects and IODP-Mission Specific Platform (MSP) expeditions takes place in two phases. During the drilling phase, drilling, curation, logging, and basic scientific data are captured at the drill site. In the post-drilling phase the detailed measurements, descriptions, images and log data for the split cores are captured within a laboratory setting and the data subsequently transferred to the long-term data storage system. Here we show how a flexible and modular designed information system has been developed over the course of continental and ocean drilling projects.

The Drilling Information System DIS

Development of the Drilling Information System (DIS) by the Operational Support Group (OSG) ICDP at the GeoForschungsZentrum (GFZ) Potsdam began in 1996. The first field test was conducted in 1998 during the ICDP Long Valley Exploratory Well project. Since then, the DIS has been used by many ICDP-supported projects and has been improved and adapted to match new requirements.

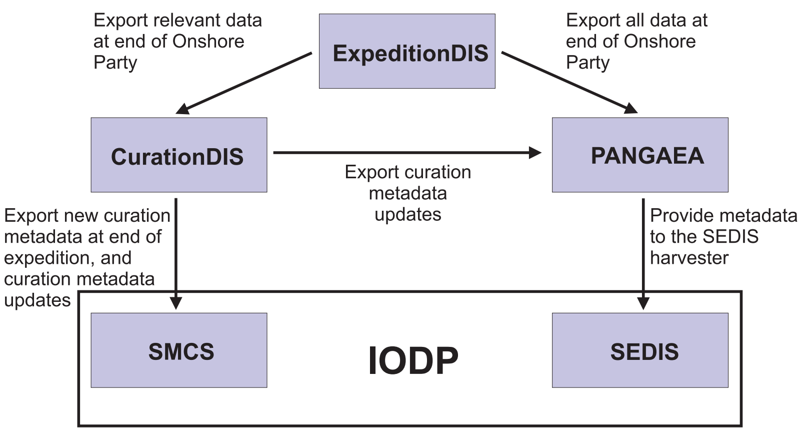

Figure 1. The general data flow of the IODP-MSP data management. The ExpeditionDIS using a common database kernel and expedition-specific tables provides scientific data to PANGAEA®, and inventory and sample data to the CurationDIS. The CurationDIS exports curation metadata to PANGAEA® and the Sample Materials Curation System SMCS, whereas PANGAEA® provides information to the Scientific Earth Drilling Information Service (SEDIS).

ICDP lake drilling projects and IODP-MSP expeditions have quite similar requirements for a data management system. It has to be mobile, easy to configure and capable of being deployed quickly on small- to medium-sized drilling platforms of opportunity. It also has to be suitable for deploying in one or more laboratories during the post-drilling data capture phase. The ExpeditionDIS was especially designed to meet these requirements (Conze et al., 2004).

Development of the ExpeditionDIS for IODP-MSP expeditions began in 2002, and the first version was used for Expedition 302 – Arctic Coring Expedition (ACEX) in 2004. It was then modified and enhanced for IODP Expedition 310—Tahiti Sea-Level in 2005, and will be used for IODP Expedition 313—New Jersey Shallow Shelf scheduled for 2007.

Another component of the DIS, the CurationDIS has been developed for use in the Bremen Core Repository (BCR, Bremen, Germany) to manage cores and samples from IODP-MSP expeditions. It will be linked into the IODP Sample Materials Curation System (SMCS) currently under development within IODP (Fig. 1).

Technical Details and Data Model

The DIS allows the user to build customized data management systems and environments for drilling projects. It has a graphical user interface, a Web interface, tools to define, generate, and administer data structures, and other elements necessary for a drilling information management system. A central component of the DIS is a set of generic data structures (templates) and dictionaries for scientific drilling purposes. These can be adapted and modified to meet specific project needs, (e.g., cuttings data, hard-rock core data, long-term monitoring data and engineering data). The graphical user interface is used to generate input forms, report templates and data views. Other tools allow the user to build specific data import modules, and to generate customized Web-pages documenting progress during the project. To visualize data, the DIS generates Scalable Vector Graphics, which are used in tools such as the Downhole-

Measurement-Profile-Builder and the Lithological-Profile-Builder.

The deployment of the DIS is highly scalable, ranging from a standalone installation on a laptop with runtime versions of MS Access and MS SQL Server, to a client-server installation with one or more DIS database servers and several client computers. The client computers can either be connected directly to the DIS server on the network, or through the XDIS web interface.

A typical setup for a project requires one DIS server computer hosting the database and several DIS clients for data input and data retrieval (Fig.2). These are connected to form a local intranet. The DIS server can also be accessed via the Internet if a connection is available. Optical core scanning devices such as the DMT CoreScan® Color or the smartcube® smartCIS™ (Camera Image Scanner) can be integrated into the network to allow core images and related metadata to be loaded directly into the database. Other data collected by the GEOTEK MultiSensor CoreLogger (MSCL) can be uploaded into the database through special interfaces.

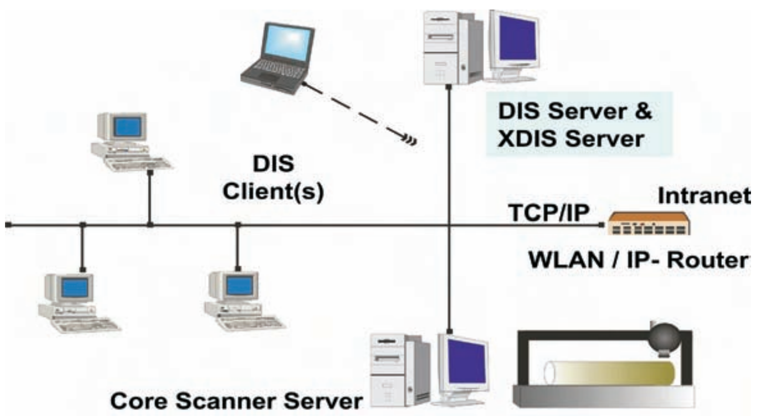

Figure 2. Typical network setup with one DIS/XDIS server and a number of DIS clients connected by a local area network and an optional Internet uplink. A core scanner device can be included as DIS client as well.

The ExpeditionDIS data model is compatible with the other IODP databases, PANGAEA® and the lake coring database LacCore (University of Minneapolis, Minn., U.S.A.). Because of this compatibility, ICDP adopted the same data model for its land and lake drilling projects in 2005.

Experience from Drilling Expeditions

The ExpeditionDIS has been used for three expeditions: IODP Expedition 302 - ACEX in 2004, IODP Expedition 310 - Tahiti Sea Level in 2005 and the ICDP Lake Petén Itzá Scientific Drilling Project in 2006. The offshore drilling phase of Expedition 302 was unique in terms of both the working environment and the use of multiple platforms (Moran et al., 2006). At the same time, it was a challenging testbed for the data management system, as it was the first deployment of the ExpeditionDIS requiring capture, management and sharing of data between the *Vidar Viking* and the *Oden* (Fig. 3). On the *Vidar Viking* drillship, cores and samples were curated, whole cores were logged using the GEOTEK MSCL and ephemeral properties were measured. The core catchers and selected samples were transferred to the *Oden* where they were described and photographed.

ExpeditionDIS systems were installed on both ships, each with its own DIS server and DIS clients connected to the local area network. Both systems were capable of working independently, but were synchronized, with database replication occurring between the ships using the wireless communications network that linked all three ships in the fleet. During the onshore phase at the Bremen Core Repository (BCR) in November 2004 data from 340 m of split core-sections and more than 8,000 samples were efficiently captured by the ExpeditionDIS (Fig. 4). The offshore and onshore data acquisition continued seamlessly despite the very different environmental conditions on the ships and in the core repository. Based on the ACEX experience, the ExpeditionDIS was amended with new data tables, dictionaries, forms, and reports to support coral-reef drilling during IODP-MSP Expedition 310 to Tahiti. Thirty-seven holes were drilled at twenty-two sites around Tahiti recovering 632 m of coral-reef core (Expedition 310 Scientists, 2006). During the onshore phase in Bremen the split cores were analyzed and described in detail and more than 12,500 samples were taken for further measurement and analysis, all supported by ExpeditionDIS.

The ICDP Lake Petén Itzá Scientific Drilling Project (Hodell et al., 2006) used the same ExpeditionDIS system as used by the Tahiti expedition. Two project scientists were trained as on site DIS-administrators during a five-day course. The sampling and additional measurements were performed using the core inventory documented by the ExpeditionDIS during the drilling phase.

Long-Term Archives

The concept of the DIS is that it is used only during the lifetime of a drilling project, and that on completion of the project the data are transferred to a long-term data management and access system. The ECORD Science Operator (ESO) selected the PANGAEA® ICSU World Data Center for Marine Environmental Sciences (WDC-Mare – http://www.wdc-mare.org; Diepenbroek et al., 2002) as the long-term archive for IODP-MSP data (Fig. 1). The data for the IODP-MSP expeditions are currently accessible via a data portal (http://iodp.wdc-mare.org). This MSP data as well as data from other IODP drilling platforms will be accessible through the Scientific Earth Drilling Information Service's (SEDIS) distributed search capability underpinned by a common metadata model (http://sedis.iodp.org/, Miville et al., 2006). Data from ICDP projects are transferred to the Scientific Drilling Database (SDDB, http://www.scientificdrilling.org) operated by the Data Center of GFZ Potsdam, Germany (See article on page 30–31, Klump and Conze, 2007).

Further Developments and Conclusions

The ExpeditionDIS has been proven to work as a robust, easy to maintain and use, on-site data capture and management system. Several additional data management components are planned. These include a visual core description module, a stratigraphic information module and data exchange tools.

Acknowledgements

The development of the ICDP Drilling Information System was funded by the GeoForschungsZentrum Potsdam, the German Research Foundation and ICDP. ExpeditionDIS and CurationDIS were financed by European Consortium for Ocean Research Drilling (ECORD) and ICDP.

Figure 3. The fleet convoy of Expedition 302 (ACEX). The ACEX ExpeditionDIS was installed on both the drill ship *Vidar Viking* in front, and the *Oden* serving as icebreaker and hosting laboratories in the middle, synchronized via a WLAN connection. The icebreaker *Sovetskiy Soyuz* is in the background.

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Figure 4. Documentation and sampling of ACEX cores at the former Bremen Core Repository using the ACEX ExpeditionDIS. Several DIS clients were used for the input of visual core description and sample curation data.

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Related Web Links

http://www.icdp-online.org
http://www.iodp.org
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Retooling Ocean Drilling Science into Earth Science Educational Resources

by Leslie Peart and Ann Klaus

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Integrating robust and relevant earth science content into higher education earth science courses is a primary objective shared by high school, undergraduate, and graduate level educators. Developing a strong educational outreach network to increase accessibility to the Integrated Ocean Drilling Program (IODP) scientific and technological accomplishments that can be used by earth science educators is a central outreach objective for the United States Implementing Organization (USIO). To marry these objectives, the Joint Oceanographic Institutions (JOI), through the USIO and the United States Science Support Program (USSSP) has created a Web portal designed specifically for K-16 educators that contains curriculum activities and background materials based on data and samples that have been generated during forty years of scientific ocean drilling.

> *"A central challenge for college and university educators is to create truly meaningful, thoughtful, and purposeful exercises or projects that engage our students with real data and real-world scientific problems, that expose them to the interdisciplinary scientific tools and technologies to solve problems, and that instill the sense of scientific discovery as a process involving teamwork. The rewards are clear—excitement, confidence, creativity, and retention. The educational materials posted on the* JOI Learning *Website provide a sampling of hands-on exercises based on scientific ocean drilling data, which can be adapted for undergraduate or graduate courses."*
>
> *—Dr. R. Mark Leckie, Department of Geosciences, University of Massachusetts, U.S.A.*

The *JOI Learning* Web site, www.joilearning.org, has achieved wide national recognition including the U.S. National Science Digital Library and the U.S. Digital Library for Earth System Education, and provides an easy-to-use portal for science educators to access content related to platform operations, drilling and engineering technology, and results from IODP, ODP (Ocean Drilling Program), and the DSDP (Deep Sea Drilling Project) scientific research expeditions. The site includes classroom activities, posters, multimedia files, career profiles, and professional development opportunities. Classroom activities can be browsed by audience (elementary, secondary, and post-secondary), content standards, or alphabetic listing. Based on the philosophy of Teaching for Science, Learning for Life™, these programs help educators to teach about Earth using

Samples of Educational Tools and Activities at *JOI Learning* (www.joilearning.org)

CLASSROOM ACTIVITIES (available in Flash and PDF):

Plate Tectonics

Plate Tectonics and Contributions from Scientific Ocean Drilling: Going Back to the Original Data: Introduce your students to the original data that proved the plate tectonic theory through an examination of the original scientific data generated during DSDP Leg 3 in the South Atlantic. For Grades 9–12 and Undergraduate.

Rocks and Minerals

Core Description and Lithostratigraphy: Enter the world of a sedimentologist aboard the *JOIDES Resolution* as your students learn how scientists describe and sample sediment cores in the Core Lab. For Grades 9–12 and Undergraduate.

Geologic Time

How old is it? Part 1: Biostratigraphy & Part 2: Magnetostratigraphy (Paleomagnetism) and the Geomagnetic Polarity Timescale: Let your students imagine being a micropaleontologist for a day and learn how to use microfossils to obtain ages for cores. They will learn how paleomagnetism is used to accurately date hard rock cores onboard the *JOIDES Resolution*. For Grades 9–12 and Undergraduate.

Climate Change

Abrupt Events of the Past 70 Million Years: Evidence from Scientific Ocean Drilling: Analyze evidence of climate change and use the data to provide evidence for abrupt climate changes at critical times in Earth's history. For Grades 9–12 and Undergraduate.

High Resolution Marine Ice Core and Marine Sediment Records: Archives of Orbital Oscillations (Milankovitch Cyclicity) in Climate: Discover Milankovitch cycles as your class unravels the data that define climate cycles that are controlled by the orbit of the Earth. For Grades 9–12 and Undergraduate.

Paleomagnetism

A Rocky Timescale 1: Help your students understand how a paleomagnetic record is recorded in rocks and deciphered by scientists through this exercise where they measure and record declination in model cores. For Grades 5–8 and 9–12.

Geophysics

Why Did They Drill There?: Let your students imagine being a scientist writing a proposal to carry out scientific ocean drilling. This activity guides students through the drill site location decision-making process. For Grades 9–12 and Undergraduate.

Engineering

A "Bit" of Engineering: This new twist on an old earth science coring activity provides an opportunity to look at ocean drilling through the eyes of the driller and the engineer by testing three different drilling tools on a variety of ocean bottom substrates. For Grades 5–8.

Chemistry

All Caged Up: This inquiry-based activity on methane hydrates allows students to model two clathrate structures commonly found in methane hydrates, challenging them to learn about gas laws, hydrogen bonding, and chemical formation. For Grades 5–12.

(continued on next page➔)

education disciplines from chemistry, physics, biology, and math to engineering and technology to reading and writing. The *JOI Learning* materials and curricular activities are generated through collaborations with scientists that have extensive research and teaching experience in fields related to ocean drilling science, classroom and museum science educators with academic backgrounds in geology, and *JOI Learning* staff.

Materials have been generated through programs such as the School of Rock Expedition, which utilized the drilling platform *JOIDES Resolution* as a science and educational learning laboratory for informal and formal educators for (see *Scientific Drilling* No. 3, September 2006, page 62, for a description of the expedition). The educators working with experienced scientists on previously recovered deep sea cores and published data from fifty-six drill sites greatly increased their knowledge about ocean drilling and created new ways to communicate ocean drilling science results to target audiences. (See Table 1.)

Over the course of the past year, participants in this program have developed ten new college-level activities, fifteen pre-college activities, twenty career profiles, nine instructional laboratory demonstration videos, and one instructional poster (see sidebar) that are available on the *JOI Learning* Web site. Professional development related to the program was also conducted at local, regional, and national levels, disseminating information about *JOI Learning* resources to K-16 earth science educators. Thus far, thirty outreach events have been conducted, ranging from short talks and presentations to posters at scientific conferences, a short course at GSA, workshops at science education conferences, and a 5-day graduate course for teachers at Western Michigan University. Early evaluations suggest the School of Rock Expedition program could impact as many as 300,000 US students over the next five years. This program will serve as a template for future educator-focused expeditions aboard the IODP-USIO Phase 2 riserless drilling vessel

Figure 1. Educators describe core on the *JOIDES Resolution* during the School of Rock Expedition.

Don't Try This at Home: Follow the fun as a teacher journals her experiences teaching about methane hydrates. This activity helps teachers foster a class-wide discussion to form a question and hypothesis and to design an experiment to discover what methane hydrates are and how they relate to the gas laws. For Grades 9–12.

Geography

It's a Small World After All: Let students test their geographic and cultural knowledge as they learn about the great diversity of people living and working aboard the *JOIDES Resolution*. For Grades K–12.

POSTERS:

A Bolt from the Blue: This poster illustrates the chemical formation of gas-bearing ice-like structures deep below the world's oceans and outlines the structure and sources of methane hydrates, introducing fundamentals for advanced chemistry and/or Earth system science courses.

Microfossils: The Ocean's Storytellers: Use this poster and related activities to simulate the identification and use of microfossils to examine past climate change. Poster features microphotographs from DSDP and ODP cores.

MULTIMEDIA:

History of Our Planet Revealed: Stories Only Rocks Can Tell: Which technology and the scientific techniques are used to read the history of the Earth from ocean floor sediments and rocks? How are scientists using the holes we have drilled in the seafloor to measure active processes that are controlling our planet today? A lecture presented by Dr. Paul J. Fox, Director, IODP-USIO Science Services, TAMU, to the National Congress for Science Education in August 2005.

Underwater Re-entry: Scientists frequently want to re-enter boreholes that were drilled during an expedition. This short video shows the drill string latching onto a re-entry cone during an ODP Leg.

Tripping Pipe: Watch the process of "tripping pipe" (the term used for the connecting or disconnecting 30 meter sections of drill pipe) in action on the *JOIDES Resolution*.

Shipboard Laboratory Briefs: Explore the unique scientific laboratories onboard the *JOIDES Resolution* and learn about the instruments used in each laboratory, the types of measurements made, and how the data are used by scientists to study Earth's history.

School of Rock Expedition: The School of Rock Expedition Web site links undergraduate and precollege activities with a wealth of supplemental resources. Check out the Q&A section for questions and answers about shipboard research and scientific ocean drilling in written and video form; the "Where in the World?" section for an online interactive about latitude and longitude; and "High S.E.A. Adventures with Mr. Buchholtz" videotaped lessons and demonstrations from the labs on board the *JOIDES Resolution.*

Career Profiles: Through an interactive photo mosaic that depicts the *JOIDES Resolution*, download or access 20 one-page career profiles that highlight some of the diverse careers available in the IODP program.

FUTURE PROFESSIONAL DEVELOPMENT OPPORTUNITIES:

Future professional development opportunities will include more science and curriculum development programs for teachers and faculty either via sailing on the *JOIDES Resolution* through the "Teacher at Sea" and "School of Rock" programs; or at the IODP core repositories, conferences, or other university laboratory settings. Scientists interested in participating in these programs as faculty should contact Leslie Peart (Director, Education, lpeart@joiscience.org).

Table 1. Connecting scientific themes with ocean drilling data

Topic	DSDP, ODP, IODP Data from Leg/Expedition
Plate Tectonics – Paradigm Overview	DSDP 3
Marine Sediments – Lithostratigraphy Drilling, receiving and describing sediment core	ODP 130, 145, 204, 206; IODP 303
Microfossils – Biostratigraphy Describing marine sediments and sampling sediment core	ODP 130, 145, 198, 202, 204, 206; IODP 303
Paleomagnetism – Magnetostratigraphy Earth's magnetic field Geomagnetic Polarity Time Scale (GPTS)	ODP 198, 199, 202
Geohydrology – Introduction to CORKS Monitoring fluid flow at spreading centers	IODP 301
Geophysics – Seismic Stratigraphy Site selection Sea level change	ODP 149, 150, 173, 174A, 208
Carbonate Geochemistry Carbonate analysis	ODP 130, 145, 206
Ocean Crust Drilling curating describing basement core	ODP 206
Abrupt Events – Deep Time Examples Cretaceous/Paleogene (K/P) boundary Paleocene/Eocene Thermal Maximum (PETM) Eocene/Oligocene (E/O) boundary interval	ODP 171B, 189, 198, 199, 207, 208
Climate Cyclicity Milankovitch (orbital) cycles Suborbital cycles (Heinrich events, Dansgaard-Oeschger oscillations)	DSDP 94; ODP 108, 143B, 154, 162, 165, 177, 198, 199
Post-cruise Research Example Reconstructing paleoclimate	ODP 152

Notes: See Leckie, et al. (2006) for specific site and hole resources from these ocean drilling legs/expeditions. Access these data via http://www.iodp.org/access-data/.

as well as for hands-on programs held at the IODP-USIO repository and other university laboratory settings.

Other ocean drilling-related curricular activities on the *JOI Learning* site have been developed by teachers participating in the USIO's Teacher at Sea Program. Through this program, middle and high school teachers are invited to participate in full expeditions where they work side-by-side with the expedition scientists and are required to produce educational content related to the program that will be added to the *JOI Learning* library. Examples of teacher-generated products include Laboratory Briefs that describe the function of each shipboard lab (http://www.joilearning.org/classroom/lab_briefs.html) and the Expedition 309 poster, "The 'Hole' Story about Ocean Cores (http://www.joilearning.org/images/309_poster_lg.jpg)."

Much of the content of the *JOI Learning* resources are appropriate for higher education audiences, and soon a portal specifically designed for this audience will be added to the site and continue to be expanded during Phase 2 of IODP. These activities are available for international use by anyone who is interested in using them. We encourage undergraduate and graduate educators to drill down into the resources on the *JOI Learning* site and integrate them into earth science courses. We also invite educators to contact *JOI Learning* if you are interested in contributing undergraduate or graduate activities or work with the *JOI Learning* staff on future ocean drilling science education programs.

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Web Link

www.joilearning.org

The Deep Sea Frontier: A New European Research Initiative

by Amelie Winkler, Jürgen Mienert, Catherine Mevel, and Sören Dürr

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Introduction

The deep sea and the deep marine seafloor form an extensive and complex bio-geosphere system. It modulates global climate and global ocean circulation, contains many of today's and tomorrow's marine resources, and hosts a partly unknown, but significant part of earth's biosphere. The Deep Sea Frontier Initiative is a new European research initiative in which the three research communities of ocean drilling, ocean margin research, and seafloor observatories will combine forces to substantially advance our knowledge base in areas such as (geo)hazards, global climate change and the sustainable exploitation of biological and geological resources of the deep sea and its floor.

Scientific drilling into the ocean floor is fundamental to the study of deep sea floor processes, because it provides the only access to deep and direct sampling and *in situ* monitoring of the ocean subsurface. Drilling projects, however, should be prepared with a multi-disciplinary and multi-tool approach. The European Consortium for Ocean Research Drilling (ECORD) therefore approached other research programs in Europe involved in paleoclimate studies (IMAGES), ocean margin research (EUROMARGINS, HERMES) and seafloor observation (ESONET) to develop a joint European program on deep-sea science. ECORD is supported by the European Commission through an ERANet, the ECORDNet, of which one specific goal is to establish and strengthen co-operation with other programs and research communities.

Bathymodiolus azoricus mussels at the Rainbow hydrothermal field, Mid-Atlantic ridge. Copyright ATOS/IFREMER

A workshop was held in Naples, Italy, 1–2 June 2006, to identify research needs and new research targets in European marine sciences. Invitations were issued to scientists from Europe and Canada, and to representatives from the petroleum industry, as well as the European funding agencies. Splitting up into separate working groups a total of seventy participants discussed the six main topics related to the investigation of the deep sea:

Topics

- History, monitoring and prediction of geohazards

Seismic activity represents a major hazard for parts of southern Europe. Low stability of volcano flanks along the Mid-Atlantic ridge and continental margin slope instability is a hazard for coastal communities if associated with tsunami generation. Submarine slides can as well be a threat to sea-bed installations. The goal of this research is a better understanding of processes leading to hazardous events, mapping of risk sites in European waters, modeling geohazards, and conduct a risk assessment for European waters.

- Geosphere-biosphere interactions affecting margins, oceans and the atmosphere

Greenhouse gases such as methane and carbon dioxide form or escape naturally from the seabed and may have a substantial influence on the biosphere and on atmospheric changes. Much of these gases are bound by bacterial communities inside the deep sea floor. However, it remains unclear how much greenhouse gas eventually enters the atmosphere. Quantification of the respective processes in the seafloor and in the water column and the role of the ocean in the carbon cycle is therefore of high priority in research.

- Long-term climatic control and feed-backs in the deep-sea environment

The Earth's climate system responds to the rising concentration of greenhouse gases in the atmosphere in a complex and poorly understood way. The deep-sea floor provides the largest continuous archive and reference frame for predicting future climate change by allowing an investigation of Earth's climate system dynamics in the past at decadal to million-year timescales.

- Evolution of deep-sea ecosystems: functioning, diversity and conservation

The biota of the deep sea floor remains largely unexplored. Only a small fraction has been sampled spatially, and even fewer areas have been sampled temporally. Industrial fisheries worldwide progressively target their activities into the deep oceans. In addition, new types of chemosynthetic ecosystems that feed on fluid vents on the seafloor have been formed on continental margins and at mid-ocean ridges. Integrated investigations of how they are distributed and how they link with the geological processes controlling fluid venting will throw light on their sensitivity to direct and indirect human impact and global change.

- The deep sea landscape: sediment transport and fluxes

The seafloor landscape (or seascape) is modified by a variety of processes active during timespans from literally instantaneous to millions of years. Climate-driven sea level oscillations, oceanic currents, tectonic settings, fluid- and sediment flow all contribute to the shaping of the deep sea floor. In addition, human activity significantly affects sediment transport and particle flux. Prospective research in this field should be multi-disciplinary, covering wide temporal and spatial ranges and apply new improved and efficient technologies for high resolution *in situ* data gathering within the water column, the seafloor and the subseafloor.

- Sustainable exploitation of deep sea resources

Established fisheries and hydrocarbon extraction are moving rapidly and steadily downslope as shallower and better accessible resources become depleted. The current and anticipated economic activity in Europe's deep water however, will lead to user conflicts. To properly address these issues and establish functional management strategies, data from different sources must be integrated, including oceanographic, geophysical, geological, hydrological, biological, social and economical data.

Road Map Investigating the Deep Seafloor

The workshop participants recognized that a concerted and multi-scale approach involving forefront research groups from different laboratories and disciplines and the best technologies and research platforms available, is key to success in this research initiative. High resolution geophysical and geological mapping and imaging of the seabed and associated biomass, laboratories at the seafloor and in the water column, drilling the subsurface, deploying observatories on the seabed and in boreholes to monitor long-term variations, will all be essential activities that need coordination at all levels.

In order to meet these new challenges, the infrastructure and capability of European marine geoscience and technology on the deep sea floor is to be significantly improved. Key areas will include technologies to sample the deep subseafloor biosphere by drilling with the Integrated Ocean Drilling Program (IODP), the capability within the academic geoscience community to collect 3-D seismic reflection data, a research strategy to address the marine methane cycle, the mapping of geohazards and risk mitigation, prediction of climate change and its impact on ecology and society, and the sustainable exploitation of deep sea resources.

Rimicaris exoculata shrimps on hydrothermal chimneys at the Rainbow field, Mid-Atlantic ridge. Copyright ATOS/IFREMER

The Deep Sea Frontier initiative is rooted as a multinational activity building up environmental research in context of the Framework Programs (FP7 and beyond) of the European Commission. Based on the outcome of the workshop a "Foresight Paper" on strategies for deep sea research in the next decade is planned to be published in mid 2007 (see Web Link below).

Contact

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Related Web Link

http://www.ecord.org/enet/deepsea-frontier.html

Lake Van Drilling Project: A Long Continental Record in Eastern Turkey

by Thomas Litt, Sebastian Krastel, Sefer Örçen, and Mustafa Karabiyikoglu

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An international research group is proposing a new research initiative, the Lake Van Drilling Project 'PaleoVan' within the framework of the International Continental Scientific Drilling Program (ICDP). The project mainly aims at obtaining high-resolution paleoclimate records from lacustrine sediments, where biotic and abiotic parameters provide proxy climate data. Lake Van in Turkey has the potential to yield long continental records covering several glacial-interglacial cycles from annually-laminated sediments, hence making the lake a key site for the investigation of the Quaternary climate evolution in the Near East.

To exploit this potential, an ICDP workshop was held in Van, Turkey on 6–9 June 2006, organized by the Institute of Paleontology, University of Bonn (Germany), and hosted by the University of Van (Turkey), with funding from the ICDP. Thirty-five researchers from twelve countries took part in the meeting, including representatives of the ICDP and Drilling, Observation and Sampling of the Earths Continental Crust (DOSECC). The workshop reviewed existing data and set priorities for an ICDP drilling proposal to obtain deep cores from the lake.

Lake Van is on a high plateau in eastern Anatolia (Fig. 1). Extending for 130 km WSW-ENE, it has a surface area of 3500 km^2, a volume of 580 km^3, and a maximum depth of 450 m. The present lake level is 1650 m above sea level. The climate of the area is continental, with hot and dry summers and cold winters. The Lake Van drainage basin covers 16,000 km^2 and lies within the eastern part of the larger Muş Basin. Lake Van water is highly alkaline with a pH of up to 9.8. Salinity is 22%, and the calcium concentration is only 4 mg L^{-1} (Landmann et al. 1996). The southern shore is formed by the Bitlis massif (3500 m above sea level), and the areas north and west of the lake are dominated by the large volcanoes Nemrut and Süphan. Lavas and/or pyroclastic flows sourced in the Nemrut volcano may have built the dam that now separates Lake Van from the rest of the Muş Basin. Rivers within the Lake Van basin discharge water and sediment into the lake, which has no outflow today. Lake Van is the fourth-largest terminal lake in the world and is long known as a very active seismic zone. About thirty earthquakes with magnitude ≥5.0 have occurred in the vicinity of Lake Van since 1900.

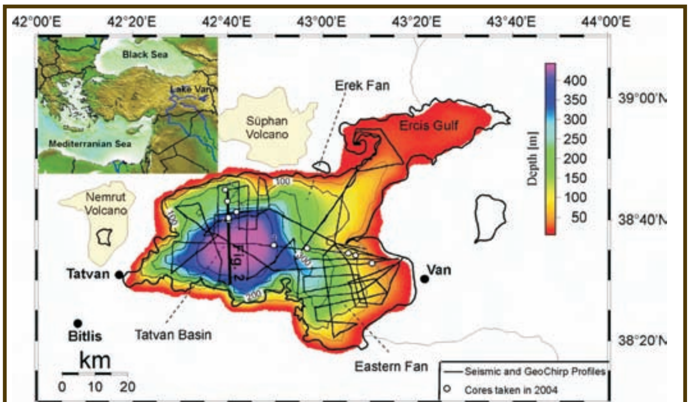

Figure 1. Lake Van, Turkey. Pre-site survey 2004: Seismic lines (fifty profiles, 850 km) and ten coring sites.

Interpretations of existing datasets obtained during the last decades were presented at the workshop. Shallow sediment cores provided evidence of an annually-laminated varve sequence. High resolution hydrochemical, geochemical, geological, and biological investigations of Lake Van in the seventies (Kempe & Degens, 1978) were continued in 1990 during a German-Swiss expedition (EAWAG Zürich, Switzerland; University Hamburg, Germany) (Landmann et al., 1996; Wick et al., 2003). Initial reconstruction of the frequency, duration, and rate of climate change in eastern Anatolia during the last 12,500 years is based on varve counting in these cores. Continuous records of varve thickness, geochemistry, stable isotopes, and pollen indicate several different climate phases (Wick et al., 2003). At least eleven volcanic ash layers have been described in these records (Landmann et al., 1996).

So far, however, it has only been possible to core to depths down to 10 m below the lake bottom, recovering Weichselian late glacial and Holocene material. Therefore, the ICDP focus program funded by the German Research Foundation financed a geophysical survey in combination with a coring campaign to prepare for a deeper lake drilling. The geophysical survey was carried out in June 2004. Fifty seismic profiles were collected, with a total length of ~850 km (Fig. 1). The new seismic net covers most of the lake and clearly proves the possibility to recover long continuous cores from Lake Van. Based on the seismic results, ten different locations in water depth up to 420 m were cored (24 July to 10 August 2004) to a maximum depth of 10 m below the lake floor. A specially designed deep-water piston corer was used to obtain cores longer than those obtained by the previously deployed Kullenberg piston corer system. Successful operation in water depths as deep as 400 m was a milestone in testing this new coring system. In addition, a Kullenberg piston corer was used to recover a set of multiple cores along the seismic lines. Short cores of the uppermost 1.5 m were taken at all drilling locations by a gravity corer to obtain undisturbed samples of the uppermost soft, water-rich sediments.

The initial results of the geophysical processing and multidisciplinary scientific work on the new cores, including magnetic susceptibility, physical properties, stable isotopes, XRF scans, and pollen and spores analyses, were also presented during the workshop. The drilling site of one of the new cores, VAN04-2 (375 m water depth), was identified as a potential ICDP drilling site in the seismic data, as it reaches deeper in time than all Lake Van cores obtained before (Figs. 2 and 3), probably spanning the last 20,000 years. There is no evidence of aragonite crusts or similar layers that would indicate extreme low stands in this part of the basin between the last glacial maximum and the present as proposed by some researchers. The laminated record appears to be one of continuous sedimentation. Seismic records suggest that at this water depth, long continuous records of up to 500ka should be present (Fig. 2).

Specific goals as determined by the workshop will be to reconstruct the following: (1) paleoclimate in a sensitive semiarid region based on transfer functions for pollen, and stable isotopes as well as modeling; (2) climate variability in space and time based on teleconnection with other high-resolution records such as ice cores and marine sequences; (3) dynamics of lake level fluctuations and hydrogeological development; (4) formation and age of Lake Van; (5) history of volcanism and volcanic activities based on tephrostratigraphy; (6) variations of the earth-magnetic field; (7) tectonic, paleoseismic, and earthquake activities; and (8) interactions between man and environment since prehistoric times. An ICDP drilling proposal addressing these topics at Lake Van will be submitted to the ICDP in 2007.

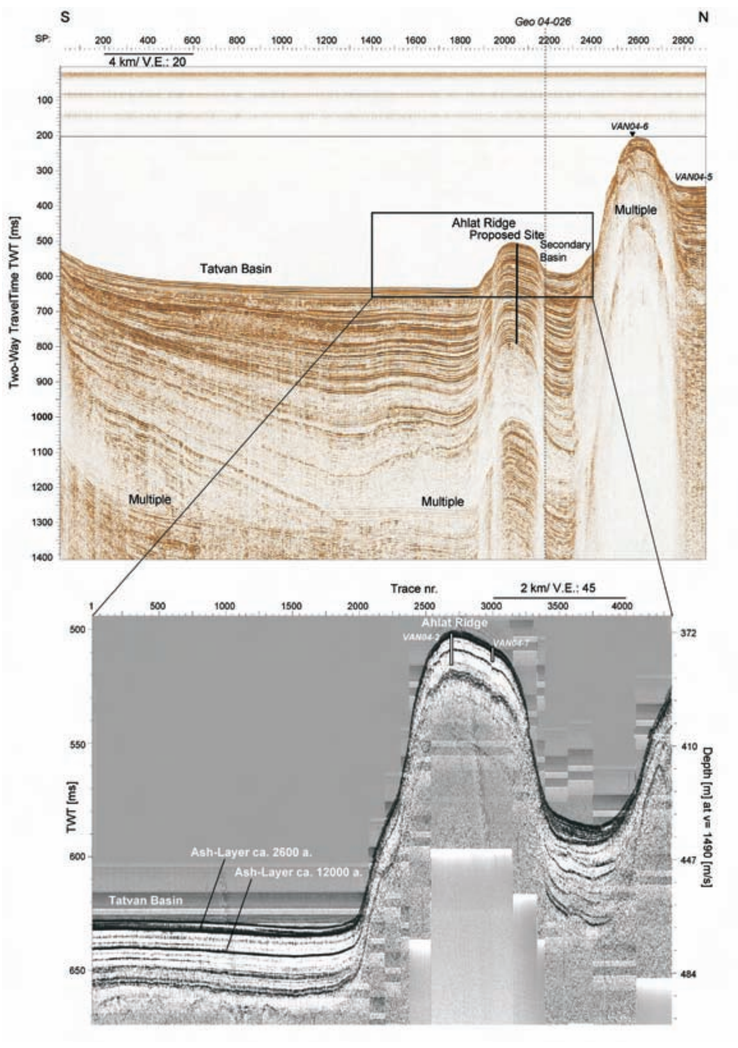

Figure 2. Stack (top) and part of Geochirp Profile GeoB04-007 (bottom) across the Tat-Van Basin. The ages for the ash layers are taken from Landmann et al. (1996). See Fig. 1 for location of the profile and Fig. 3 for sediment core VAN04-02.

Figure 3. Core photo from core Site 2 obtained in 2004 (VAN04-2-4, segment 4) with annually laminated lacustrine sediments and intercalated tephra layers.

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Related Web Link

http://van.icdp-online.org

Joint IODP/ICDP Scientific Drilling of the Chicxulub Impact Crater

by Jo Morgan, Gail Christeson, Sean Gulick, Richard Grieve, Jaime Urrutia, Penny Barton, Mario Rebolledo, and Jay Melosh

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Impacts of asteroids and comets on planets are fundamental processes in the solar system. Relatively few pristine craters are preserved on the Earth because of the vigorous endogenic geologic processes that affect its surface. Nonetheless, only terrestrial craters can provide us with direct observations on the subsurface structure of impact craters, the dynamics of crater formation, and the effect on the planetary environment as preserved in the geological record.

The Chicxulub impact crater in Mexico (Fig. 1) is unique in the terrestrial impact record. Its association with the Cretaceous–Paleocene (K-P) mass extinction has generated great interest, but the precise environmental effects and associated extinction mechanisms remain a matter of some debate over several decades. Chicxulub is also the best preserved large impact crater on Earth and is the only known terrestrial impact structure with a demonstrable topographic peak ring (Figs. 2 and 3). Peak rings are common features of large craters on the terrestrial planets yet their process of formation is poorly understood. At all other large terrestrial craters, erosion and/or tectonic deformation have removed the evidence of a peak ring, should one have existed. Chicxulub is, thus, the only crater where the peak ring can be imaged and sampled.

The Chicxulub structure, partly located onshore and partly offshore, is buried below post-impact sediments (Figs. 1 and 2). Thus, while geophysical imaging of the structure is possible (Fig.3), sampling of the structure can only be done through drilling and coring. Onshore there are several deep, but mainly uncored, industry wells (S-1, C-1 and Y6 in Fig. 1), a number of shallow holes drilled by Universidad Nacional Autonóma de México (U-1), and one deep International Continental Scientific Drilling Program (ICDP) hole, Yaxcopoil-1 (Yax-1), drilled in 2002. No holes have yet been drilled offshore (Figs. 1 and 2).

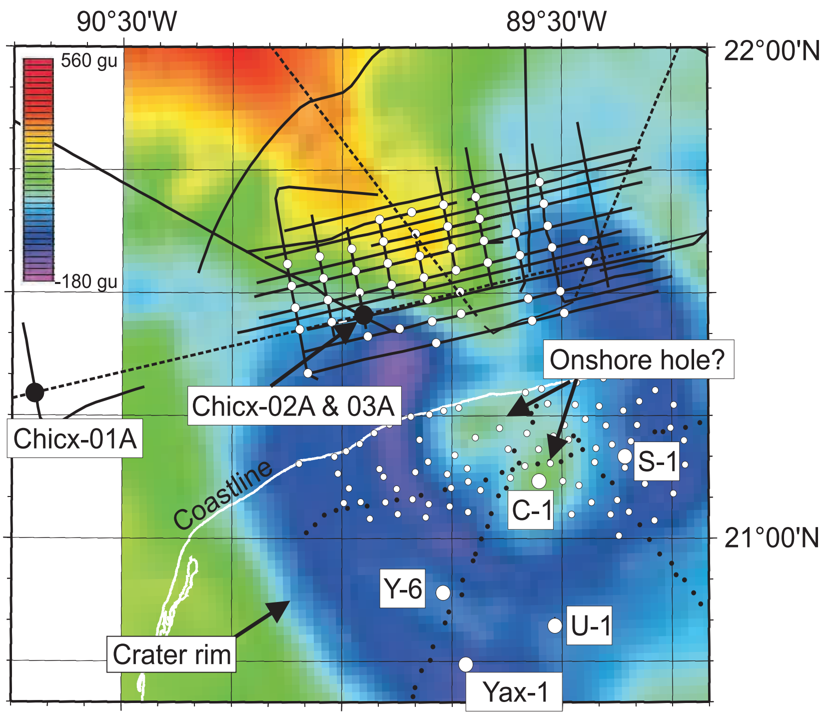

Figure 1. Solid black lines, 2005 marine seismic survey. Dashed black lines, 1996 survey. Locations of offshore and onshore seismometers are shown for the 2005 survey (small white dots) and the 1996 survey (small black dots). Large white dots mark PeMex drill holes (C-1, S-1, Y-6), UNAM hole U-1, and ICDP hole Yax-1. Black dots mark proposed offshore IODP drill sites. Background color depicts Bouguer gravity.

A workshop on future scientific drilling of the Chicxulub impact crater was held at GeoForschungsZentrum Potsdam (GFZ), Germany on 11–12 September 2006. The workshop was sponsored by the Integrated Ocean Drilling Program (IODP) and ICDP. Fifty scientists from eleven countries attended the workshop. During the first day keynote speakers outlined the current state-of-knowledge of large impact craters (Chicxulub in particular), reviewed results from previous drilling at Chicxulub, and showed new seismic data (Figs. 1 and 3) that were acquired across the crater in 2005 (Morgan et al., 2005). On the second day potential new drill sites, their scientific priorities, and associated logistics were discussed.

Two holes were identified as critical to advancing the understanding of cratering mechanisms: i) one hole through the crater's topographic peak ring (offshore location), and ii) a second well near the crater center passing through the entire sequence of impactites, particularly the impact melt sheet, and into the uplifted crust in the center of the crater (onshore location). There was unanimous support for a joint IODP-

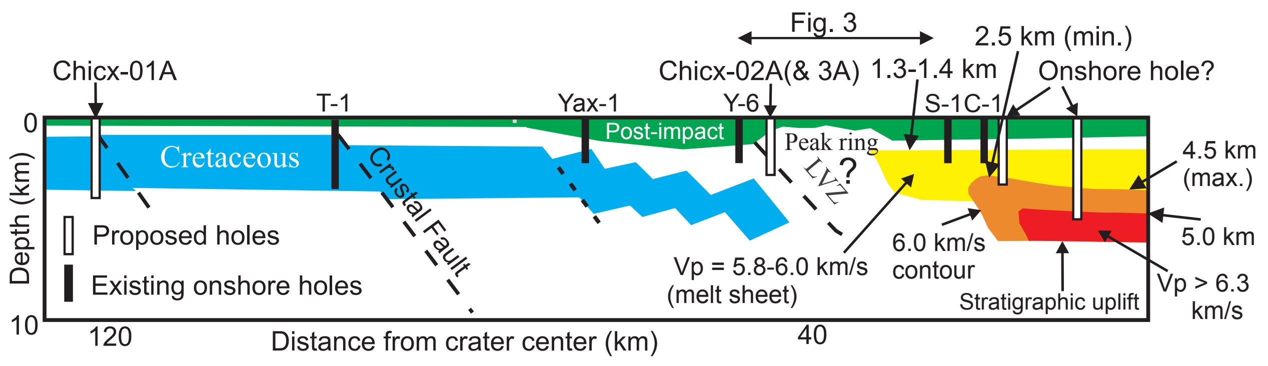

Figure 2. Proposed structure of Chicxulub Crater from geophysical data and drilling (Morgan et al., 2005). The Cretaceous, post-impact sediments, peak ring, and top of the melt sheet are all imaged on marine seismic reflection data. The shape of the melt sheet (yellow) and central uplift (red and orange) are inferred from tomographic seismic velocity data. There is a low velocity zone (LVZ) of unknown origin beneath the peak ring. Chicx-01A is a hole through intact target rocks just outside the crater, and Chicx-02A and 03 are holes through the crater's topographic peak ring.

ICDP planning and execution of the entire drilling efforts, including sample and data handling.

Offshore Drilling of the Peak Ring

Workshop participants were universally enthusiastic about drilling through the peak ring and underlying dipping reflectors. The expected lithologies of the drill hole include ~700 m of post-impact fill, and 2.3 km of peak-ring forming material (suevitic breccia, megabreccia, and/or fractured basement). From ~2.35 km depth this hole will sample a suite of dipping reflectors that can be traced from the outer edge of the peak ring to the inner edge of the slumped blocks (Figs. 2 and 3). This hole will determine the fundamental character of the lithologies above and below the dipping reflectors, the physical state of the material, and the cause of the reflectivity. We will use these data to discriminate between competing models of peak ring formation. If the peak ring material here has been overturned, as predicted by some numerical models, these reflectors may represent the boundary between outwardly collapsed central uplift and inwardly collapsed transient crater rim.

The lithological, geochemical, and structural characteristics of these Chicxulub wells will provide the first data set of this kind from the Earth, or indeed from anywhere within the solar system.

A discussion group on hydrothermal processes recognized that recent studies at large terrestrial impact craters indicate that significant hydrothermal activity is likely to occur within the peak ring. The drill core can provide information on the temperatures and composition of hydrothermal fluids and on the longevity of the system. Hydrothermal activity could also lead to a niche for hyperthermophilic bacteria with impact-induced porosity and translucence supporting colonization by cyanobacteria (Cockell et al., 2002). These studies may therefore help understanding the development of early life on Earth and possibly Mars, where impacts were more frequent in early Archean time.

Chicx-03A (Figs. 2 and 3) was chosen as the best location for a peak ring drill site. A site further towards the crater center has the potential to provide more information about the peak-ring forming material but would not reach the dipping reflectors. Conversely, a site further out from the center would reach the dipping reflectors at a shallower depth but would not necessarily sample 'typical' peak ring material.

Onshore Drilling of the Melt Sheet and Suevite

Another critical target identified by the workshop is an onshore hole near the crater center (Figs. 1 and 2). Scientific targets of this hole would be to examine the entire suevite and impact melt rock sequence, variations in the clasts with respect to amount, composition, and degree of shock in both of these impactite layers; to investigate if the melt sheet is differentiated; to search for a projectile component and its variation with depth; and to document the lithologies above and below the melt sheet, including any secondary mineralization due to hydrothermal activity. Physical properties measured within the hole, together with seismic, magnetic, and gravity data, will allow us to produce a well-constrained 3-D geophysical model of the crater, including an improved estimate of total melt volume, which is intimately connected to impact energy.

Participants agreed that this hole should be located to recover as thick a sequence of melt as possible, but also should penetrate at least 200 m into the central uplift. According to our tomographic velocity model (Fig. 2), a hole near the crater center would reach the uplifted crust at ~4.5 km depth and might be prohibitively expensive. Consequently, a more feasible location for this hole is close to the onshore uncored industry well C-1 (Fig. 1), where the melt sheet was found at a depth of ~1300 m, based on well cuttings, and where the central uplift is between 2.5 and 3.3 km subsurface.

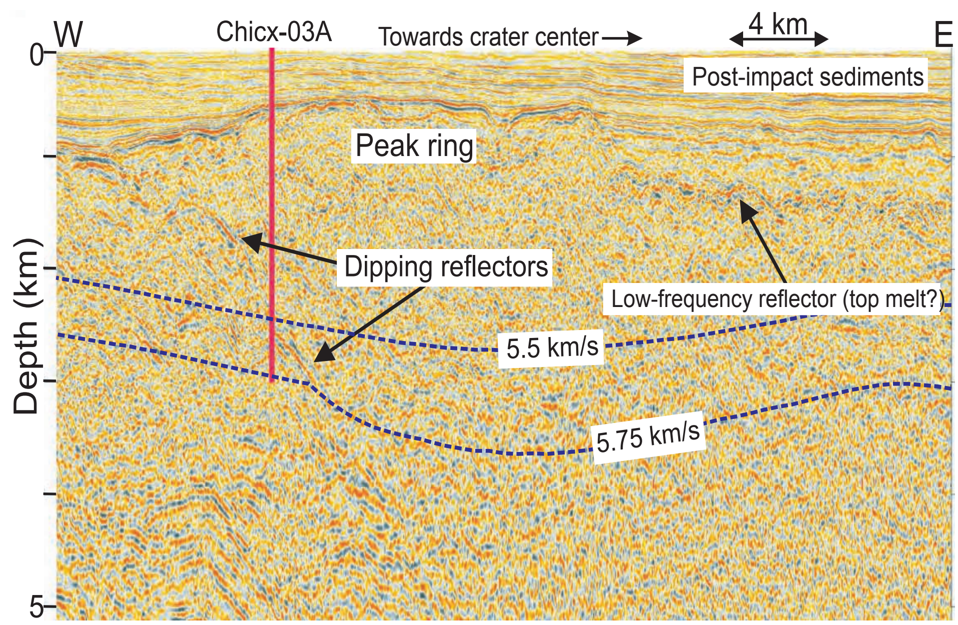

Figure 3. Newly acquired, depth-converted seismic profile Chicx-10. Thick red line shows proposed drill site Chicx-03A. The drill hole will sample ~700 m of post-impact sediments before penetrating the peak ring. A suite of dipping reflectors will be encountered at ~2.35 km depth. Dashed lines are velocity contours from our 3D tomographic velocity model. Vertical exaggeration is 4:1.

Both the onshore and offshore holes will penetrate through post-impact sediments, which are ~700 m thick in Chicx-03A and ~1100 m close to drill hole C-1, and which are likely to include impact-generated tsunami deposits, the biotic recovery with time, long-term hydrothermal activity, mineralization, and the post-impact paleoceanographic record.

The workshop participants concluded that Chicxulub crater is a unique natural laboratory that assumes a crucial role in providing information on the impact cratering process, including a possible link to niche creation for early life, and the global effect of a large-scale impact event. They also agreed that its further investigation should be pursued in a coordinated joint effort by the IODP and the ICDP.

Acknowledgments

The workshop was jointly sponsored by the International Continental Scientific Drilling Program (ICDP) and the Integrated Ocean Drilling Program Management International, Inc. (IODP-MI). The Joint Oceanographic Institutions (JOI) and Natural Environment Research Council (NERC) provided travel support for some U.S. and U.K. participants.

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Related Web Link

http://chicxulub.icdp-online.de/

Scientific Ocean Drilling Behind the Assessment of Geo-Hazards from Submarine Slides

by Angelo Camerlenghi, Roger Urgeles, Gemma Ercilla, and Warner Brückmann

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Introduction

The workshop 'Scientific Ocean Drilling Behind the Assessment of Geo-hazards from Submarine Slides' was held on 25–27 October 2006 in Barcelona (Spain). Fifty mainly European scientists and industry representatives attended from a wide spectrum of disciplines such as geophysics, stratigraphy, sedimentology, paleoceanography, marine geotechnology, geotechnical engineering, and tsunami modeling.

Submarine Slides and Scientific Drilling

Submarine slides pose societal and environmental risks to offshore infra-structures (platforms, pipelines, cables, sub-sea installations), and coastal areas including tsunamis (Fig. 1), and they can dramatically change the marine environment. Triggering mechanisms include earthquakes, gas hydrate dissociation, instability of volcanic flanks, and fluid flow. Research on submarine slides may also help understand paleoseismicity, climate change, and sedimentary facies on basin evolution relevant to hydrocarbon reservoir characterization.

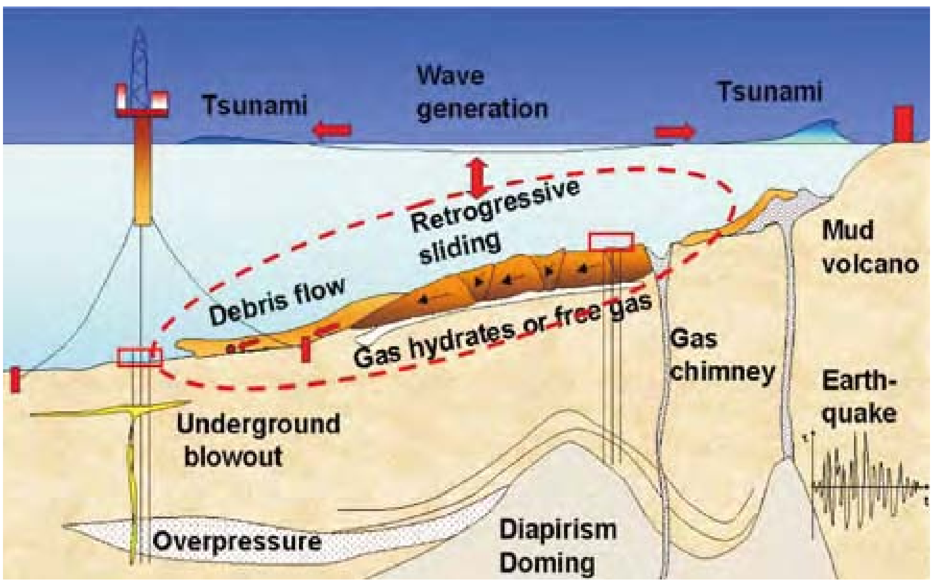

Figure 1. Offshore geohazards. Submarine slides generated by human activity are recognized as submarine geohazards for first party seabed structures and for third party (population) because of their potential to generate tsunamis. Submarine slides are known to occur also as a consequence of the natural evolution of continental margins.

The Storegga Slide off Norway and close to the Ormen Lange Gas Field remains the only medium to large submarine mass movement that has been investigated to confirm the geometry as well as the *in situ* stresses and their evolution at the time of failure ('Ormen Lange Project', Solheim et al., 2005). This study concluded that extensive geophysical surveys, seabed characterization, geotechnical boring, and *in situ* measurements both inside and outside the slide bodies are needed to reliably define and constrain the lateral variability of geotechnical parameters (Fig. 2). Drilling is required to address the following four questions.

What is the frequency of submarine slides? Drilling and appropriate high resolution stratigraphic and geo-chronologic tools can establish the history and frequency of submarine slope failures. Currently only a few mega events such as the Storegga Slide (roughly 8150 years old) have been dated with sufficient accuracy. Many medium and small recent submarine slides are known to have higher rates of recurrence (Hühnerbach and Masson, 2004).

What is the tsunamigenic potential of a submarine slide? Tsunami generation is controlled not only by slide geometry (slide volume, area, water depth) but also by slide kinematics (slide acceleration and velocity). Sampling and *in situ* measurements are needed to understand the rheology of the slide. Evidence suggests that shearing of the landslide mass is significantly different at its base compared to its top, which translates into a distinct profile of physical properties (Expedition 308 Scientists, 2005). Insights obtained through sampling of the failed sediments may help predict the failure dynamics of a yet stable slope.

Do precursory phenomena of slope failure exist? We need to determine which transient signs might indicate imminent slope instability and improve our capability to predict events of slope instability. Consequently, it

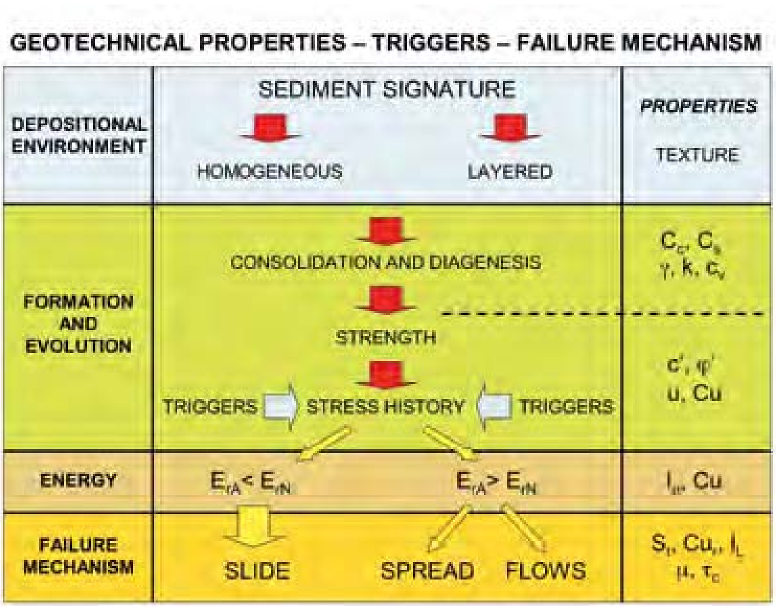

Figure 2. Conceptual relationships between marine sediment geotechnical properties, submarine slide triggers, and sediment failure mechanisms.

C_c = Compressibility index
C_s = Swelling index
γ = Unit weight
k = Hydraulic conductivity
c_v = Coefficient of consolidation

c' = Cohesion
φ' = Friction angle
u = Pore water pressure
Cu = Undrained shear strength

I_p = Plasticity index

S_t = Sensitivity
Cu_r = Remolded undrained shear strength
I_L = Liquidity index
μ = Viscosity
τ_c = Yield strength

E_{rA} = Available remolding energy
E_{rN} = Needed remolding energy

is necessary to conduct long-term monitoring of pore pressure, temperature and hole inclination in slopes where failure might occur in a relatively short term. Investigation of the geochemistry of pore fluids may tell if clay minerals such as smectite released mineral water due to shear. Drilling and monitoring are also important to describe how slow deformation of slopes (creep) occurs and to relate seismic reflection features to active sediment deformation.

What makes up weak layers in continental slope sediments? Submarine landslides are often found to be rooted at one or more stratigraphic levels. These levels likely represent a "weak layer" that plays a fundamental role in landslide initiation and in determining slide volume and geometry. In glaciated margins weak layers have been identified in contouritic deposits that were formed during interglacial periods and were rapidly buried under thick glacial-marine deposits (Bryn et al., 2005). The occurrence of weak layers in non-glaciated margins is poorly understood.

Hypotheses and Models

While a general relationship between slope instability and natural climatic cycles has been demonstrated on the Northern European margin (Solheim et al., 2005), the mechanisms behind the generation of submarine slope instability are still poorly understood because of lack of deep penetration sediment cores. There are at least two hypotheses and models that could be tested through drilling.

1. The focusing of fluids and lateral transfer of stresses can trigger slides. Two-dimensional modeling of the New Jersey margin suggests that lateral fluid flow in permeable beds under differential overburden stresses produces fluid pressures that approach the lithostatic stress where overburden is thin. This transfer of pressure may cause slope failure initiation at the base of the continental slope (Dugan and Flemings, 2000). IODP Expedition 308 tested a hydrogeologic model by which pore fluids are laterally advected under certain loading and stratigraphic conditions (Behrmann et al., 2006). Excess pore pressure in highly permeable sediments is transferred to zones of lower overburden with an important effect on slope stability. Similar pore fluid advection might be caused by glacial loading of permeable sediments (e.g., Storegga Slide or Antarctic Peninsula margin).

2. The Clathrate Gun Hypothesis (Kennett et al., 2000) states that methane emissions from gas hydrate dissociation induced by climate change and bottom water warming is related to submarine slide activity. The unroofing of buried hydrate-bearing sediments by submarine slides enhances methane emissions from the seafloor by instantaneously decreasing the confining pressure. The carbon isotope chemistry and the assemblages of benthic calcareous foraminifera close to paleo-slide heads might contain a record of paleo-methane seeps as well as other (micro) biological indicators.

Conclusions

Geohazards have mainly been addressed in scientific drilling campaigns as a complementary goal. Future and dedicated drilling experiments should address mega slides as well as small to medium slides. Understanding the mechanics of the less frequent, but potentially catastrophic, mega slides requires a large amount of site survey data and might require a multi-expedition effort. Smaller slides occur with a frequency close to that of natural hazards considered in the determination of the 500 years risk. They may cause damage to seabed installations and generate tsunami waves that, although being relatively small, may cause onshore damage and casualties in densely populated coastal regions. More than one small to medium submarine slide can be addressed effectively in one single drilling expedition, but may require a multi-platform approach supporting stratigraphic drilling, geotechnical drilling, and installation of borehole and seafloor observatories.

High-resolution seafloor mapping, possibly using deep-towed devices or remotely operated vehicles (ROV), and the integration of bathymetric and backscatter information will be necessary to obtain the best morphologic and acoustic characterization of recent slides. High-resolution 3-D seismic data acquisition will be important to define targets within the unfailed sediments, scar and detachment area, evacuation zone, and accumulation area within a slide complex. For appropriate post-cruise geotechnical analyses, the drilling system must obtain high-quality undisturbed geotechnical samples. Existing advanced piston coring and narrow kerf rotary drilling were considered most prospective for implementation on IODP drilling vessels. Long term monitoring of key parameters in boreholes (e.g., pore pressure, hole inclination, or ambient acoustic noise) can utilize the well-established Circulation Obviation Retrofit Kit (CORK) technology. A link with existing seafloor observatories initiatives was recognized as very important for remote and real-time monitoring.

Drilling to understand submarine slope instability is perceived as highly multidisciplinary. Drilling proposals should address scientific questions outlined above in a variety of geological environments. The teams of proponents should include a wide range of tsunami experts, sedimentologists, paleoceanographers, geotechnical engineers, and deep-sea observatories. The international community will further stress the importance of Geohazards research during the upcoming IODP Geohazards Workshop in Summer 2007 (see workshop announcements on page 51).

Acknowledgements

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Related Web Links

http://www.esf.org
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Fig. 1. Courtesy of Norwegian Geotechnical Institute (NGI) and the International Centre for Geohazards (ICG)
Fig. 2. by J. Locat, Laval University, Quebec, Canada.

The Campi Flegrei Deep Drilling Project

by Giuseppe De Natale, Claudia Troise, and Marco Sacchi

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Introduction

Large collapse calderas represent an extremely explosive type of volcanism with potential for global impact. Although very rare, such super-eruptions represent a serious threat to mankind. However, moderate to small eruptions from such calderas represent a major risk as well, particularly in urban areas. One example is the 1994 eruption of the Rabaul caldera which destroyed the town of Rabaul (Papua New Guinea). This event demonstrated that eruptions are possible with only minor and very short-term precursory signals, while long episodes of unrest involving uplifts on the order of up to 1 meter and intense seismicity may occur without immediate volcanic activity.

Campi Flegrei in Southern Italy is a typical example of a collapsed caldera whose surface is partially (60%) submerged (Fig. 1). It has the highest recorded ground movements not immediately followed by eruptions. First colonized by Greeks and home to the largest Mediterranean military fleet during the Roman times (Baia, on the west side of caldera), this area has the longest historical record of ground movements associated with volcanic activity, as revealed by marine incrustations and molluscs on the Roman and medieval buildings (Fig. 2 and Troise et al., 2006). The secular deformation of this area is subsidence, at a rate of about 1.5–1.7 cm yr^{-1}, with some periods of large and faster uplift (Fig. 2A). Historically, three such uplift periods are evident; the first one occurred from ca. 650 to 730 AD and the second from 1441 to 1538, while the third one is still in progress following the latest eruptions since 1969 (Fig. 2B). This recent period is characterized by episodes of very fast deformation rates, followed by periods of minor subsidence (Fig. 2C). The total uplift from 1969 to 1984 was 3.5 m, while the uplift rate in the period 1983–1984 exceeded 1 m yr^{1}. A relatively fast subsidence was recorded after 1985 until the end of 2004; since late 2005 a new uplift episode is in progress, currently reaching 4 cm, half of which in the last two months of the record (Fig. 2C).

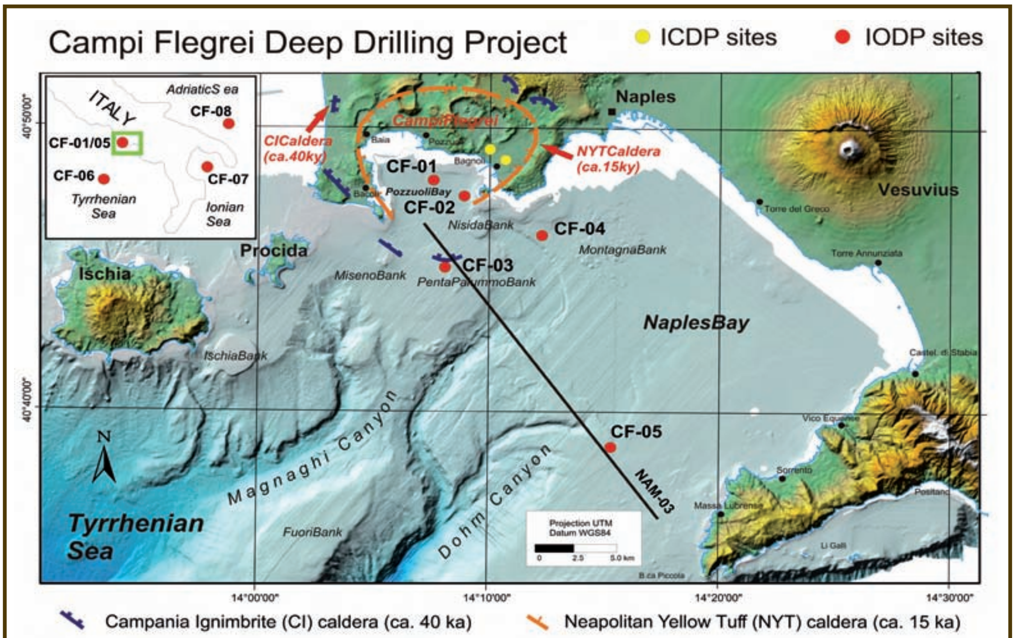

Figure 1. Planned drilling locations on land (yellow circles) and offshore (red circles). The rationale for the choice of offshore locations is described as follows: [CF-01] caldera center, in order to penetrate the structural floor of the NYT caldera (1.5–2 km) and sample the tectono-stratigraphic interval likely involved in the late stage caldera resurgence; [CF-02] (optional, or alternate) along-transect site within the NYT caldera collapse, in order to drill the caldera fill at site of minor stratigraphic thickness (~0.8–1.0 km); [CF-03] targets the external rim of the caldera and penetrates a relatively complete stratigraphic section (~0.6–0.8 km deep); [CF-04] is located just outside the hypothetical caldera collapse, in order to sample the non-collapsed stratigraphic sequence (0.8–1.0 km); [CF-05] intended to sample a Quaternary tephro-stratigraphic reference section (1 km) in a relatively undisturbed location; [CF-06–08] relatively shallow drillholes (0.4–0.6 km) are planned at distal site locations to capture major explosive events of the entire Campania volcanic district and map the regional dispersal areas to aid reconstruction of the dynamics and evolution of eruptive events.

The largest caldera-forming eruption occurred about 39,000 years ago, when grey tuff covered the whole Campania region with large flow deposits. Associated fine ashes can be traced as far away as Moscow (Russia). The most recent caldera-forming eruption (15,000 years ago) produced a yellow tuff deposited over the larger Naples region. More than sixty smaller hydromagmatically eruptions modified this area up to present time. With a history of massive volcanic eruptions and ongoing deformation, this densely urban area including the city of Naples is exposed to a very high volcanic risk.

Planning Workshop

A workshop on the 'Campi Flegrei Deep Drilling Project' was held on 13–15 November 2006 in Naples, Italy, in a location within the Campi Flegrei caldera and close to the main candidate site for on-land drilling—the Bagnoli area (Fig. 1). The workshop was among the first European efforts to assess volcanic hazard within the context of the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP). The participants presented evidence that the setting and features of the partially submerged Campi Flegrei Caldera provides an ideal natural laboratory for future joint ICDP-IODP research. About seventy scientists from nine countries representing multidisciplinary fields participated in the meeting. A plenary session was held on the first day, followed by groups for on-land and off-shore drilling working separately during the second and third days to define science targets and appropriate tools for an integrated amphibious drilling program. Important on-going ICDP and IODP drilling projects in areas with objectives and technologies of interest to the Campi Flegrei project were presented during joint sessions. These included keynotes on the regional volcanic evolution and results of previous geothermal drilling activities. The different working groups ranked main scientific objectives and elaborated the best strategies for drilling and related research in the respective fields. In addition, the development of new drilling proposals for IODP and the nurturing of existing proposals were discussed.

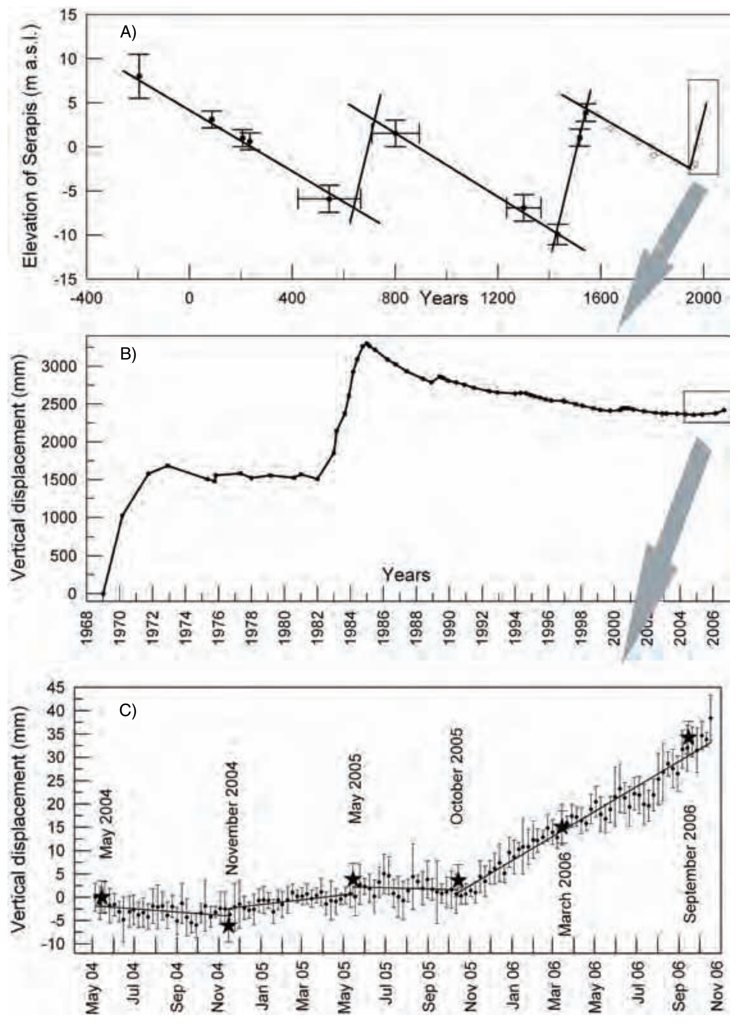

Figure 2. Ground deformation at Campi Flegrei as a function of time, at three progressive enlargements. [A] Schematic vertical movement history at Macellum in Pozzuoli, known as Serapis Temple. Black circles and white circles represent data points from various sources (see De Natale et al., 2006 and references therein). [B] Vertical ground displacements as recorded at Pozzuoli Harbor by leveling data during 1969–2006. [C] Detail of vertical displacement from May 2004 to October 2006 as recorded from CGPS (dots) and precision leveling at bench mark in Pozzuoli harbor (stars). Errors on CGPS and leveling data (1σ) are also shown (Redrawn after Troise et al., 2006).

Main Conclusion

A key conclusion from the workshop was that the combined on-land and off-shore drilling is required to address the following key scientific objectives: 1) to understand the link between shallow fluids and magmatic systems generating unrest and feeding extremely explosive eruptions, 2) to better assess the high volcanic risk in the area and to develop best strategies for risk mitigation in Campi Flegrei and in similar environments, and 3) to develop new technologies of environmental monitoring and the exploitation of geothermal energy including industrial spin-offs.

The workshop participants pointed out that in order to accomplish the main targets, a strict integration of several research fields is needed, including geology, geophysics, seismology, petrology, geochemistry, geochronology, geothermal investigations, numerical and analogue modelling, physics of the matter, and engineering. The multi-disciplinary project structure will require the combination of several work packages tied to and supporting the central tool of deep drilling and coring. For on-land drilling, the most reliable site has been identified in the area of Bagnoli (Fig.1). This site is large enough to host two drill sites—one close to the caldera rim, and the other closer to the caldera center. The first drill site on land close to the caldera rim allows for further addressing two important scientific objectives with a relatively shallow hole (<2 km): 1) understanding of the rheology of an aseismic layer which seems to represent a strongly fractured and water-saturated medium with a sharp transition down towards a seismically active, gas-saturated medium, and 2) direct observation of mechanical and fluid-dynamical properties across the caldera borders which have been interpreted as sites of focused stress and strain with dominant ductile (aseismic) behavior (De Natale et al., 2006).

The second and deeper drill hole on land closer to the caldera center will additionally target the deeper geothermal system and heat flow (including the critical temperature point, estimated at 2.5–3 km depth) to measure the purely conductive gradient and to extrapolate magmatic temperatures (target depth = 4–4.5 km).

In order to study in detail the properties of the rocks and the geothermal system for the whole depth extension at the caldera center (position CF-1), this drilling should be complemented by an off-shore site into the caldera center down to the critical point at this position (estimated depth ~2 km). A second (maximum 1-km-deep) off-shore site is planned just outside the caldera border (southeast of the Posillipo hill, in the Gulf of Naples, position CF-4 in Fig. 1). The goal will be to compare the different structure and rheology across the caldera border and to sample a complete section of the older volcanic successions. Additional off-shore sites are planned to complete the reconstruction of Campi Flegrei and larger Campania volcanism by deep drilling, as specified in the caption of Figure 1.

Acknowledgements

The Campi Flegrei Workshop was mainly sponsored by ICDP and the ESF within the framework of Magellan workshops. The meeting was organized and partially supported by INGV and IAMC-CNR with the contribution of AMRA-Campania, University of Naples Federico II, and INOA-CNR.

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Upcoming Workshops

11th Annual Continental Scientific Drilling Workshop

3–5 June 2007, Washington, D.C., Application Deadline: 5 May 2007

Drilling in the Earth's continental crust allows studies of otherwise inaccessible subsurface geological processes and structures. Drilling has led to many important geological discoveries on paleoclimate, impacts, volcanoes, mantle plumes, active faults, etc. The workshop, sponsored by Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC), will include presentations on international and multidisciplinary drilling projects and topics. A field trip and a reception are also planned to allow participants ample opportunity to exchange ideas. All geoscientists interested in using drilling as a tool are invited.

Limited funding is available for travel to help offset the cost associated with workshop participation. More information: http://www.dosecc.org/

Contact: David Zur (dzur@dosecc.org)

Rift to Ridge '07

28–29 June 2007, National Oceanography Centre, Southampton, UK.

The U.K. IODP organizes a workshop dedicated to North Atlantic rift - drift evolution under the influence of the Iceland Hotspot. The influence of a hotspot on the development of an oceanic basin from rifting through to mid-ocean ridge spreading will be addressed at this workshop. Main topics of discussion will be the influence of the mantle on rifting and break-up geometries, the mantle circulation and hotspot phenomena, the consequences for crustal-scale horizontal and vertical tectonics, the influence on the structure of oceanic crust and the geometry of seafloor spreading, and linkages between basin evolution and oceanographic circulation, and thus to climate change. The goals are to coordinate proposed and planned IODP efforts aimed at addressing North Atlantic evolution, to stimulate new proposals and identify mechanisms to lever funding, and to address the hotspot phenomenon and its influence on ocean basin evolution in a 'joined-up' fashion.

To participate, please register online at http://www.noc.soton.ac.uk/gg/rift_ridge07/

International Workshop on Large Igneous Provinces

21–26 July 2007, Coleraine, Northern Ireland, Application deadline: 15 March 2007

The outcome of this international workshop will guide the Integrated Ocean Drilling Program in addressing the objectives in the IODP Initial Science Plan regarding processes associated with and consequences of large igneous province (LIP) emplacement.

Workshop participants will define key scientific objectives of investigating transient large igneous provinces through drilling; establishing an integrated and interdisciplinary, long-term, global strategy for addressing fundamental LIP science questions; and identifying the technological requirements for achieving these objectives. Problems associated with intraplate and rifted margin LIPs will be considered. Participants will include scientists with a broad range of expertise including geophysics, paleoclimatology, paleoceanography, environmental modeling, micropaleontology, physical volcanology, planetary geology, tectonics, geochemistry, and petrology. Research methods range from field and laboratory observation to simulation. Drilling engineers will participate and provide information about enhanced drilling, logging, and long-term borehole monitoring capabilities of IODP.

Support for travel expenses is available for approximately eighty participants. Interested scientists and engineers from all countries should apply on-line. Special consideration will be made for advanced students and early-career scientists.

More information and a registration form is available online at http://www.iodp.org/workshops/

Contact: Kelly Kryc (kkryc@iodp.org).

Workshop Addressing Geologic Hazards Through Ocean Drilling

26–30 August 2007, Portland, Oregon, U.S.A.
Application deadline: 1 April 2007

The oceans are the sources of some of the most severe geologic hazards, including large tsunami-generating earthquakes, submarine landslides, and explosive volcanic eruptions. We seek to extract and read the geologic record of such events in marine sediments and to monitor material properties and associated physical processes. This workshop will bring together an interdisciplinary pool of scientists and engineers from research institutions, universities, and companies for an open and detailed exchange of results, ideas, and experiences to better characterize and understand the causes and consequences of oceanic geologic hazards.

Goals of the workshop are to (a) review the current state of community knowledge, (b) define outstanding research questions that can be addressed through scientific ocean drilling, (c) establish scientific priorities, (d) identify potential drilling targets, (e) evaluate existing technologies and scientific approaches, and (f) recommend the development of new instruments and new deployment strategies. This exchange will enhance international collaborations and stimulate teams of proponents to develop competitive IODP proposals addressing oceanic geologic hazards.

IODP and other sponsoring agencies will support travel and expenses for approximately eighty participants. Interested scientists and engineers from all countries are advised to apply online at www.iodp.org/workshops. Selected participants will be contacted by the steering committee. Places will be reserved for advanced students and early career scientists. For more information, please visit the workshop Web page.

More information and registration at http://www.iodp.org /workshops/

Contact: Kelly Kryc (kkryc@iodp.org).

IODP Topic Symposium on North Atlantic and Arctic Climate Variability

15–16 August 2007, University Campus Bremen, Germany

IODP plans the first topical symposium in 2007 under the subject "North Atlantic and Arctic Climate Variability". It will take place at the University of Bremen and is organized by Professor Dr. Gerold Wefer, MARUM. There will be four main topics, each filled with invited lectures and posters:

- Millennial-Scale Climate Dynamics
- Milankovitch Scale Climate Variability
- Evolution of Northern Hemisphere Glaciation
- Extreme Warm Events

Registration and payment logistics for the topical symposium will be organized by IODP. See more details published in March 2007 at www.iodp.org.

IODP / ECORD Summer School on Paleoceanography

13–24 August 2007, University of Bremen, Germany.

Co-sponsored by the European Consortium for Ocean Research Drilling (ECORD), the Bremen graduate school GLOMAR, and the Research Center Ocean Margins (RCOM), Bremen, Germany, a two-week summer school on paleoceanography for thirty PhD students and young postdocs is offered at the Center for Marine Environmental Sciences (MARUM), University of Bremen. Using the facilities of the IODP Bremen Core Repository, a practical on core logging and time-series analysis techniques will be combined with lectures and interactive discussions on the paleoceanography of the Cretaceous to Cenozoic Oceans. A focus will be put on key topics of ocean heat transport and nutrient cycles, on recent developments in integrated stratigraphy, and on recent studies of North Atlantic and Arctic Ocean climate variability.

A tuition fee of 100 enros is requested. Scholarships for travel and accommodation are available on request.

To apply, please send e-mail to: gratmeyer@marum.de before 31 March 2007.

IODP and ECORD kindly invite you to take part in the following events scheduled at the EGU General Assembly 2007 in Vienna, Austria (15–20 April, 2007):

ECORD-IODP booth (Monday to Friday, 16–20 April) - a meeting point for everyone looking for information about scientific ocean drilling, and **joint ICDP-IODP Townhall** meeting (Tuesday, 17 April)—"Scientific Drilling: News from the Integrated Ocean Drilling Program and the International Continental Drilling Program". Detailed information is regularly posted on the ECORD web site (http://www.ecord.org/) and also available on request at: ema@ipgp.jussieu.fr

Looking forward to welcoming you in Vienna!

Chikyu Successfully Tested by Scientists and Industry

The Japan Agency for Marine-Earth Science and Technology's (JAMSTEC) deep-water riser vessel *Chikyu* successfully passed full-scale deep-water drilling tests off Japan and off the coast of Kenya. All aspects of drilling, downhole logging, and coring except rotary coring in riser mode operation have been tested.

The *Chikyu* shakedown cruise was carried out off the Shimokita area, northern Japan. The coring operation test was conducted by riserless drilling with the HPCS (Hydraulic Piston Coring System) and ESCS (Extended Shoe Coring System) at a pilot hole, C9001C, in 1180 m water depth, penetrating to 365 mbsf and recovering forty cores (386 m in total length). The riser drilling test at the main hole, C9001D, finished at a depth of 647 mbsf; cuttings samples were obtained from twenty-five intervals between 527–647 mbsf. In the laboratory, we conducted a wide array of experiments related to processing, curating, and measuring cores, as well as discrete sample data collection and processing, using real cores and cuttings samples in order to demonstrate the ability to meet IODP operation standards. In order to assist in evaluation of laboratory operations, twenty-seven technical and scientific advisors from Japan and abroad were invited onboard to work with cores in the laboratories and report their findings of laboratory functionality, procedure or core handling etc. Part of the test drilling was conducted under very severe weather conditions, which proved *Chikyu* to be a very stable and powerful platform.

A number of useful observations were made regarding core and laboratory functions. The onboard measurement results also provided several interesting scientific findings. Recovered cores, as well as cuttings samples, are chiefly composed of diatomaceous silty clay, with common intercalations of tephra and sand layers as subordinate components in the upper and lowermost parts. The age for the bottom of Hole C9001C is estimated to around 650 ka. The lithofacies of the lower part are almost lacking in tephra and sand layers, which suggests limited volcanic activity in the hinterland during this period, presumably 400 – 600 ka. Based on the relative abundance of diatoms and terrigenous clastic material, the silty clay can be divided into two types that interchange periodically, probably reflecting climate change influenced by the Milankovich Cycle.

On the *Chikyu's* drill floor.

Chikyu operating offshore about 300 km northeast of Mombasa, Kenya. Photo credit Woodside Energy (Kenya) PTY LTD.

After completing the Shimokita shakedown drilling in 1200 m of water, *Chikyu* began the Overseas Drilling Shakedown (ODS) cruise on 1 November 2006. Actual drilling operations off Kenya, East Africa began in early December 2006. *Chikyu* has successfully set the BOP and riser pipe at a water depth of 2200 m under more than 2 knots (kt) of strong sea current, and the drilling depth reached about 2700 mbsf (about 4900 m below the rotary table). These are some of the ODS System Integration Tests (SIT) of *Chikyu*'s drilling systems. After completing riser drilling off Kenya, *Chikyu* shifted to Australian waters for more deep water riser drilling. The ODS tests are done in a collaboration with the hydrocarbon exploration industry and include full-scale deep-water industry riser drilling including geophysical downhole logging. Coring is not routinely done.

Visual core description (VCD) lab work onboard the *Chikyu*.

ANDRILL Project Reaches 1284.87 meters at McMurdo Sound

The Antarctic Geological Drilling (ANDRILL) Program drilled to a new record depth of 1284.87 meters below the seafloor from the site on the Ross Ice Shelf (McMurdo Sound) near Scott Base in Antarctica on 26 December. The operations team of twenty-five drillers, engineers, and support staff started preparing in mid-October, and began drilling in early November. The target depth was 1200 meters, which they had hoped to reach before Christmas. The final depth broke the previous record of 999.1 meters set in 2000 in Prydz Bay by the Ocean Drilling Program's drill ship, the *JOIDES Resolution*.

The drilling had a core recovery of 98 percent. The cores contain alternations of clastic glacial and marine, biogenic, and volcangenic sediments. Diatoms and abundant ashes in combination with magnetostratigraphy will allow precise dating. It is estimated that the bottom of the hole is well within the upper Miocene or older. So far, the drill cores tell a story of a dynamic Antarctic ice sheet advancing and retreating more than 50 times during the last 5 My. Some of the disappearances of the ice shelf were probably during times when our planet was 2–3°C warmer than it is today.

The ANDRILL Project is a multinational collaboration comprised of more

ANDRILL camp and Mount Erebus.

ANDRILL drilling rig in low sun.

than 200 scientists, students, and educators from four nations (Germany, Italy, New Zealand, and the United States). Following-up on the Cape Roberts Drilling Project, ANDRILL strives to recover stratigraphic records from the Antarctic margin using advanced developments of Cape Roberts Project technology. The chief objective is to drill back in time to recover a history of paleoenvironmental changes that will guide our understanding of how fast, how large, and how frequent were glacial and interglacial changes in the Antarctica region. Future scenarios of global warming require guidance and constraint from past history that will reveal potential timing, frequency, and site of future changes.

Operations and logistics for ANDRILL are managed by Antarctica New Zealand. The scientific research is administered and coordinated through the ANDRILL Science Management Office, located at the University of Nebraska-Lincoln (UNL). The U.S. part of the project is funded in large part by a $12.9 million National Science Foundation grant to a consortium of five universities headed by UNL and Northern Illinois and also including Florida State, Massachusetts-Amherst, and Ohio State. More information about ANDRILL as well as a complete description of the recent drilling project is available at www.andrill.org.

ANDRILL is now planning for the second drilling project in southern McMurdo Sound later this year (October to December 2007). The stratigraphic objective will be to recover a middle Miocene to Recent core record that will detail a proximal history of Antarctic ice sheet behavior back through the mid-Miocene Climatic Optimum.

New Jersey Shallow Shelf - Expedition 313

Expedition 313 is planned for the summer of 2007. This expedition, co-funded by ICDP and part of a major margin transect with previously drilled land- and deep-water sites, will focus on Early to mid-Miocene (~24–14 Myr old) siliciclastic sequences to estimate the timing and magnitudes of eustatic sea-level changes, and determine the relationship between sea-level change and sedimentary architecture (See www.ecord.org/exp/new-jersey/313). Intense Antarctic glaciation at the beginning of the Early Miocene and a mid-Miocene 'Climatic Optimum' when ice sheets were at a relative minimum likely have forced short-term sea-level changes. In addition, the New Jersey margin offers rapid depositional rates, tectonic stability, and well-preserved fossils for age control. In addition, there exists a large set of seismic and borehole data constraining the geologic setting from the coastal plain across the shelf to the slope and rise. Expedition 313 is different from these previous missions in that it targets the shallow shelf which is very sensitive to sea-level change, and the technology aboard the mission specific platform of choice is well-suited for recovering sand-prone shelf sediments.

HSDP Reached 3519.5 m Final Depth

On 10 February 2007, coring operations in the Hawaii Science Drilling Project, HSDP have been completed at a total depth of 3519.5 m. In the final phase of the HSDP drilling from December 2006 on, 177 m have been drilled.

Core from 3507.6 m depth with pillow breccia clasts surrounded by a matrix of blue-green clay; beneath the breccia (left) is a layer composed almost entirely of clay.

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Starting in summer 2007, the IODP and the ICDP will change the *Scientific Drilling* subscription policy. We will require subscribers to renew their subscription every three years. This can be done by logging into the database and reviewing the subscription data. We also ask everyone to register an e-mail address so we scan inform you when your subscription expires. To continue your current subscription, please do the following.

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Your subscription will be renewed automatically once you log in. If you encounter problems, lose the envelope with the subscription ID, or have questions or comments, send e-mail to *journal@iodp-mi-sapporo.org*.

Thank you very much for your help in keeping the data up to date. *Scientific Drilling* will continue to come free of charge, bringing you information on the IODP, the ICDP, and other scientific drilling programs.

Schedules

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

IODP INTEGRATED OCEAN DRILLING PROGRAM

The riser vessel *Chikyu* will start drilling in the Nankai Trough in late 2007.
See http://www.iodp.org/expeditions/ for the most up-to-date IODP drilling schedule.

icdp

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

	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–Feb. '07	Hilo, Hawaii, U.S.A.
3	Lake El'gygytgyn Drilling Project	sched.for '07–'08	Chukotka, Russia
4	Iceland Deep Drilling Project	sched. for '07–'10	Krafla, Iceland
5	Fennoscandian Arctic Russia-Drilling Early Earth Project	May–Oct. '07	Kola, Russia
6	New Jersey Continental Shelf **	sched. for summer '07	Offshore New Jersey, U.S.A.

* Subsequent Borehole Monitoring until 2020
** IODP-ICDP joint project