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# Scientific Drilling

Reports on Deep Earth Sampling and Monitoring


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Published by the Integrated Ocean Drilling Program with the International Continental Scientific Drilling Program

# Editorial Preface

## Dear Reader:

In 2009 scientific ocean drilling for the first time utilized the capabililty to conduct closed hole, mud-assisted drilling through the deployment of a 'riser'—an approximately 0.5-meter-diameter steel pipe that connects the drilling vessel to a cased hole in the seafloor. The riser vessel *Chikyu* (front page) now offers the scientific community this capability that opens up totally new research opportunities. Sadly, not science, but the 2010 environmental disaster in the Gulf of Mexico made words like riser, blow-out-preventer, casing, cementing of holes, etc. part of everyone's vocabulary. But we can be proud that after four decades and more than 1300 scientific drill sites in the oceans, not a single drop of oil have been released into the ocean due to scientific drilling.

The new technology does not stop with riser drilling, but includes *in situ* observatories providing time-series of fluid flow, pressure, stress and strain, or seismic activity, thereby extending our science from records of the past to observing "Earth in motion". Preparations for observatories to be established within the seismogenic zone offshore Japan is reported on p.4. The material brought into the seismogenic zone by the Philippine Sea plate pushing below Japan is reported on p.14. When fully completed, this project will allow observations to be made very close to the zone where truly large earthquakes occur, and, therefore, like the Hubble telescope, provide a much clearer picture of the processes that take place.

The revolutionary finding that life *on* Earth in fact is complemented by deep microbial life *in* the Earth is addressed on pp.35 and 46. ICDP has now extended the search for deep microbial life—previously mainly demonstrated from below the ocean seafloor—to continental areas such as sediments below lakes. This discovery of potentially large, subsurface life and carbon reservoir follows in the heels of the major carbon reservoir identified by scientific drilling over the last decade or so—the vast gas hydrate deposits along many continental margins, in the climate-sensitive Arctic Ocean and at the bottom of Lake Baikal. As gas hydrates sublimate at elevated temperatures, potential doomsday scenarios could be envisaged if global warming triggered a cascading effect of greenhouse gas release. Scientific drilling allowed for detecting this phenomenon, and it is a key tool to predict the consequences of future sea-level rise (p.26).

In Iceland, attempts are made to harvest $CO_2$ neutral energy by deep drilling with required new technology into very hot crust (p.40). If more globally successful, this pioneering effort could lead to less dependence on fossil fuels. And finally, on p.56, a recent workshop reports on how and where to possibly fulfill the 50-year-old quest to drill through the entire ocean crust and into the underlying mantle. With riser drilling onboard *Chikyu*, this is now becoming a real possibility.

**Hans Christian Larsen**
**Editor-in-Chief**

**Ulrich Harms**
**Editor**

**Front Cover:** *Chikyu* at night before departure for the Nankai Trough, one of the most active earthquake zones in the world. (11 May 2009, Port of Shingu, Japan)
**Left inset:** The riser tensioner. The six riser tensioner cylinders (yellow) support the riser pipe (white) in the center.



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IODP is an international marine research drilling program dedicated to advancing scientific understanding of the Earth by monitoring and sampling subseafloor 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 and ICDP Expedition Schedules

# IODP Expedition 319, NanTroSEIZE Stage 2: First IODP Riser Drilling Operations and Observatory Installation Towards Understanding Subduction Zone Seismogenesis

by Lisa McNeill, Demian Saffer, Tim Byrne, Eiichiro Araki, Sean Toczko, Nobu Eguchi, Kyoma Takahashi, and IODP Expedition 319 Scientists

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## Abstract

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a major drilling project designed to investigate fault mechanics and the seismogenic behavior of subduction zone plate boundaries. Expedition 319 is the first riser drilling operation within scientific ocean drilling. Operations included riser drilling at Site C0009 in the forearc basin above the plate boundary fault, non-riser drilling at Site C0010 across the shallow part of the megasplay fault system—which may slip during plate boundary earthquakes—and initial drilling at Site C0011 (incoming oceanic plate) for Expedition 322. At Site C0009, new methods were tested, including analysis of drill mud cuttings and gas, and *in situ* measurements of stress, pore pressure, and permeability. These results, in conjunction with earlier drilling, will provide a) the history of forearc basin development (including links to growth of the megasplay fault system and modern prism), b) the first *in situ* hydrological measurements of the plate boundary hanging wall, and c) integration of *in situ* stress measurements (orientation and magnitude) across the forearc and with depth. A vertical seismic profile (VSP) experiment provides improved constraints on the deeper structure of the subduction zone. At Site C0010, logging-while-drilling measurements indicate significant changes in fault zone and hanging wall properties over short (<5 km) along-strike distances, suggesting different burial and/or uplift history. The first borehole observatory instruments were installed at Site C0010 to monitor pressure and temperature within the megasplay fault zone, and methods of deployment of more complex observatory instruments were tested for future operations.


## Introduction

Subduction zones account for 90% of global seismic moment release, generating damaging earthquakes and tsunamis with potentially disastrous effects as exemplified by recent earthquakes in Indonesia and Chile. Understanding the processes that govern the strength and nature of slip along these plate boundary fault systems by direct sampling and measurement of *in situ* conditions is a crucial step toward evaluating earthquake and tsunami hazards. To this end, the Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) project (Tobin and Kinoshita, 2006) has been implemented, complementing other fault drilling projects worldwide (e.g., the San Andreas Fault Observatory at Depth (SAFOD) and the Taiwan-Chelungpu Drilling Project). NanTroSEIZE is a multistage program focused on understanding the mechanics of seismogenesis and rupture propagation along subduction plate boundary faults, targeting a transect of the Nankai margin offshore the Kii Peninsula, the location of the 1944 M 8.2 Tonankai earthquake (Fig. 1). The drilling program is a coordinated effort over a period of years to characterize, sample, and instrument the plate boundary system at several locations, culminating in drilling, sampling, and instrumenting the plate boundary fault near the updip limit of inferred coseismic slip, at ~6–7 km below sea-

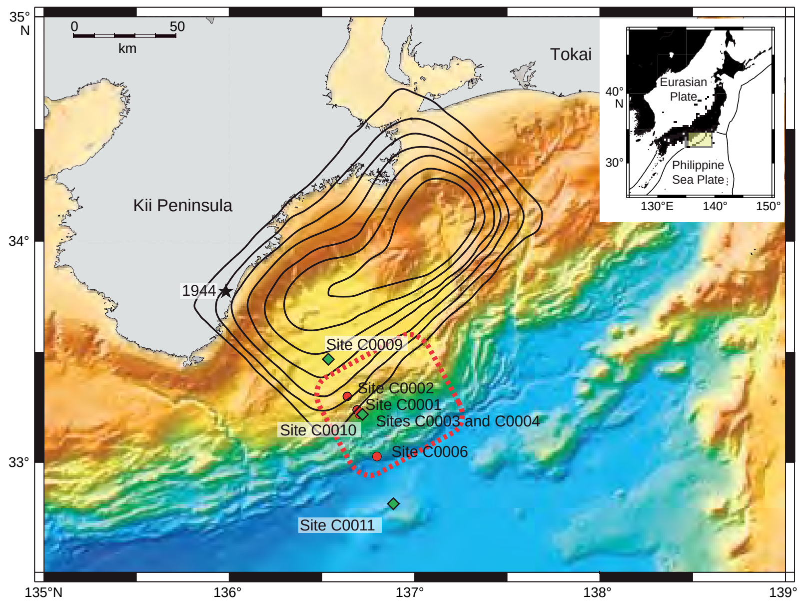


Figure 1. Map of the Nankai margin study area showing drill sites (from Stage 1 and from this expedition, including Site C0011 of Expedition 322; Underwood et al., 2010), details of 1944 plate boundary earthquake slip, and location of coseismic VLFs. See Fig. 6 and Saffer et al. (2009, 2010) for further geographic information. Contours = estimated slip from 1944 event (0.5 m intervals, increasing inwards; Kikuchi et al., 2003), red box = region of recorded VLFs (Obara and Ito, 2005). Inset shows tectonic setting.

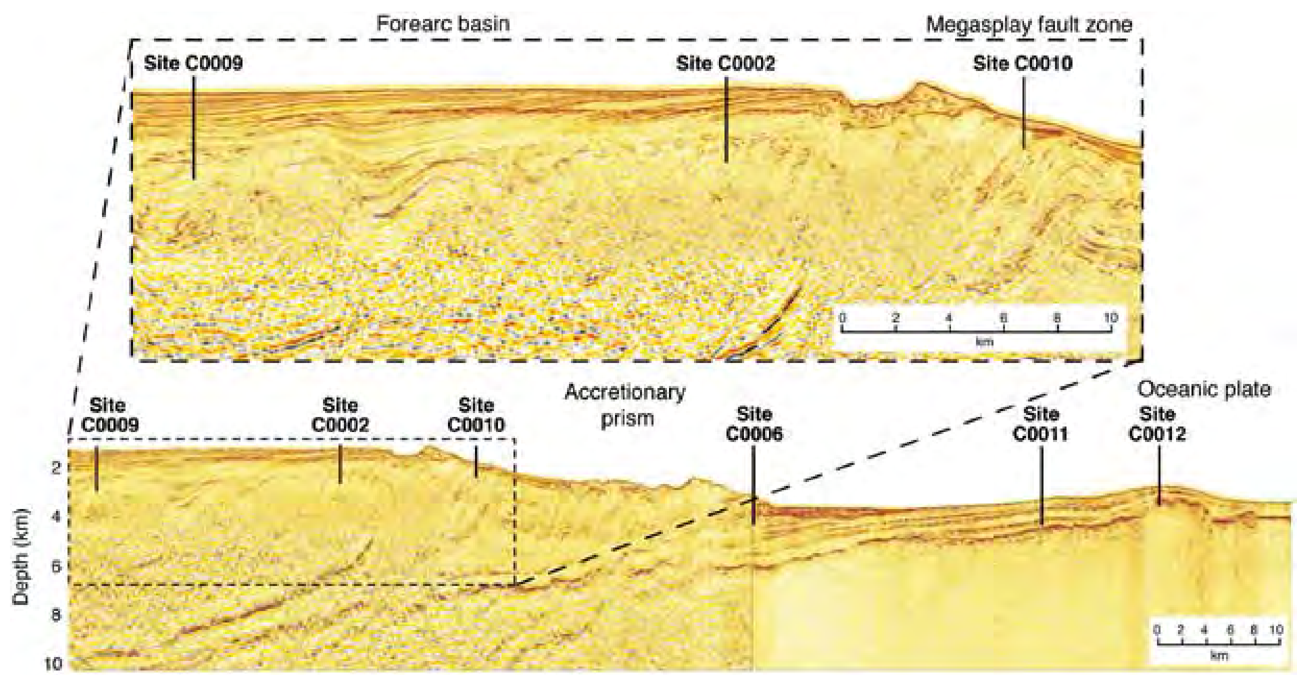


Figure 2. Seismic line across the Nankai margin from 3-D seismic reflection volume showing drill site locations (see also Saffer et al., 2009, 2010 and Fig. 5 for further details of the Kumano forearc basin structure). See Expedition 322 results for details of drilling at Sites C0011 and C0012 (Underwood et al., 2009, 2010).

floor (Tobin and Kinoshita, 2006). The main project objectives are to understand the following:

- *In situ* physical conditions and the state of stress within different parts of the subduction system during an earthquake cycle
- The mechanisms controlling the updip aseismic-seismic transition along the plate boundary fault system
- Processes of earthquake and tsunami generation and strain accumulation and release
- The mechanical strength of the plate boundary fault
- The potential role of a major fault system (termed the "megasplay" fault, Fig. 2) in accommodating earthquake slip and hence influencing tsunami generation

These objectives are being addressed through a combined program of non-riser and riser drilling and integration of linked long-term observatory, geophysical, laboratory, and numerical modeling efforts.

## The Nankai Margin

The Nankai subduction zone forms as a result of subduction of the Philippine Sea Plate beneath the Eurasian Plate at ~40–65 mm $yr^{-1}$ (Seno et al., 1993; Miyazaki and Heki, 2001; Fig. 1) and has generated M8 tsunamigenic earthquakes on identifiable segments of the margin regularly (~150–200 years) over at least the past ~1000–1500 years (Ando, 1975). The most recent earthquakes occurred in 1944 (Tonankai M 8.2) and 1946 (Nankaido M 8.3). The margin has been extensively studied using marine geophysics (including two 3-D multichannel seismic reflection volumes), ocean drilling (across three transects along the margin), passive seismology, and geodesy. The position and effects of earthquake rupture are therefore relatively well understood, and the structure of the margin is well imaged. More recently, very low frequency (VLF) earthquakes and slow slip events have also been recorded, in the shallowest and deeper parts of the subduction system, respectively (Obara and Ito, 2005; Ito et al., 2007). The region offshore the Kii peninsula is the focus of the NanTroSEIZE experiment drilling transect and marks the western end of the 1944 earthquake rupture zone (Fig. 1). The drilling transect region has been imaged with an ~11 km x 55 km 3-D seismic reflection volume (Moore et al., 2007, 2009; Bangs et al., 2009; Park et al., 2010) revealing along-strike structural variability in addition to excellent across-strike imagery. This region is also the focus of the seafloor observatory project "Dense Oceanfloor Network System for Earthquakes and Tsunamis" (DONET; http://www.jamstec.go.jp/jamstec-e/maritec/donet/) which will install seafloor instruments as part of a cabled network connected to shore. This observatory network will also connect to borehole observatory instruments installed as part of the NanTroSEIZE project (Tobin and Kinoshita, 2006) to enable longer term monitoring of seismicity, deformation, hydrological transients, pressure, and temperature.

## The NanTroSEIZE Project and Expedition 319

Shallow drilling of a series of holes across the forearc was conducted successfully during Stage 1 of the NanTroSEIZE project in late 2007 through early 2008 onboard the D/V *Chikyu* (Expeditions 314, 315, 316; Ashi et al., 2009; Kimura et al., 2009; Kinoshita et al., 2009a; Fig. 1). These expeditions collected logging-while-drilling (LWD) data (providing *in situ* measurements of physical properties and stress state) and core samples in the shallower aseismic regions of the frontal thrust and the major megasplay fault, and within the forearc basin. Stage 2 consisted of Expedition 319 (the subject of this report) and Expedition 322, conducted from May to October 2009. Expedition 322 drilled, logged, and sampled the input sedimentary section to characterize the properties of sediment that ultimately influence fault development and seismogenic behavior (Underwood et al., 2009, 2010).

Expedition 319 drilled two main sites, C0009 and C0010 (Figs. 1 and 2). Drilling operations were also started at Site C0011, contributing to Expedition 322. Site C0009 is located within the central Kumano forearc basin in the hanging wall of the locked seismogenically active plate boundary (Figs. 1 and 2) and is the site for a future long-term observatory site. Objectives were to drill, sample (cuttings and cores), and log (wireline log data) the hole, conduct downhole *in situ* measurements and a vertical seismic profile (VSP) experiment, and finally case and cement the hole for future observatory installation. The scientific objectives at Site C0009 were as follows: (1) document the lithology, structure, *in situ* properties and development of the central Kumano forearc basin (lying within the hanging wall of the seismogenic plate boundary fault); (2) collect core samples at the depth of a future potential observatory for geotechnical analysis in advance of observatory instrument installation; and (3) constrain the seismic properties of the deeper subduction zone including the plate boundary below the drill site using a two-ship VSP experiment.

Site C0010 is located ~3.5 km along strike from Site C0004 (Fig. 1, see also Fig. 6 and Saffer et al., 2010) which was drilled during Expeditions 314 and 316 (Kinoshita et al., 2009a; Kimura et al., 2009). Objectives were to drill and log the hole, install an instrument package across the fault zone (designed to collect data for a few years), and prepare for the future installation of an observatory by conducting a "'dummy"' run of an instrument package containing a strainmeter and seismometer. Logging data at this site included measurement-while-drilling (MWD) and LWD (gamma ray, resistivity-at-bit, and resistivity image data); these data were used to constrain the lithology, structural deformation, and *in situ* stress within and across the shallow section of the megasplay fault zone (Figs. 1 and 2). This site provides the opportunity to document and quantify the degree of along-strike structural variability within the megasplay fault system through comparison with Site C0004.

Expedition 319 was noteworthy because it included the first riser drilling operations in scientific ocean drilling history, as well as the first observatory installations conducted


Figure 3. Drilling tools and operations: [A] riser drilling, [B] Modular Formation Dynamics Tester wireline logging tool (single probe at top, dual packer below), [C] observatory dummy run instruments.

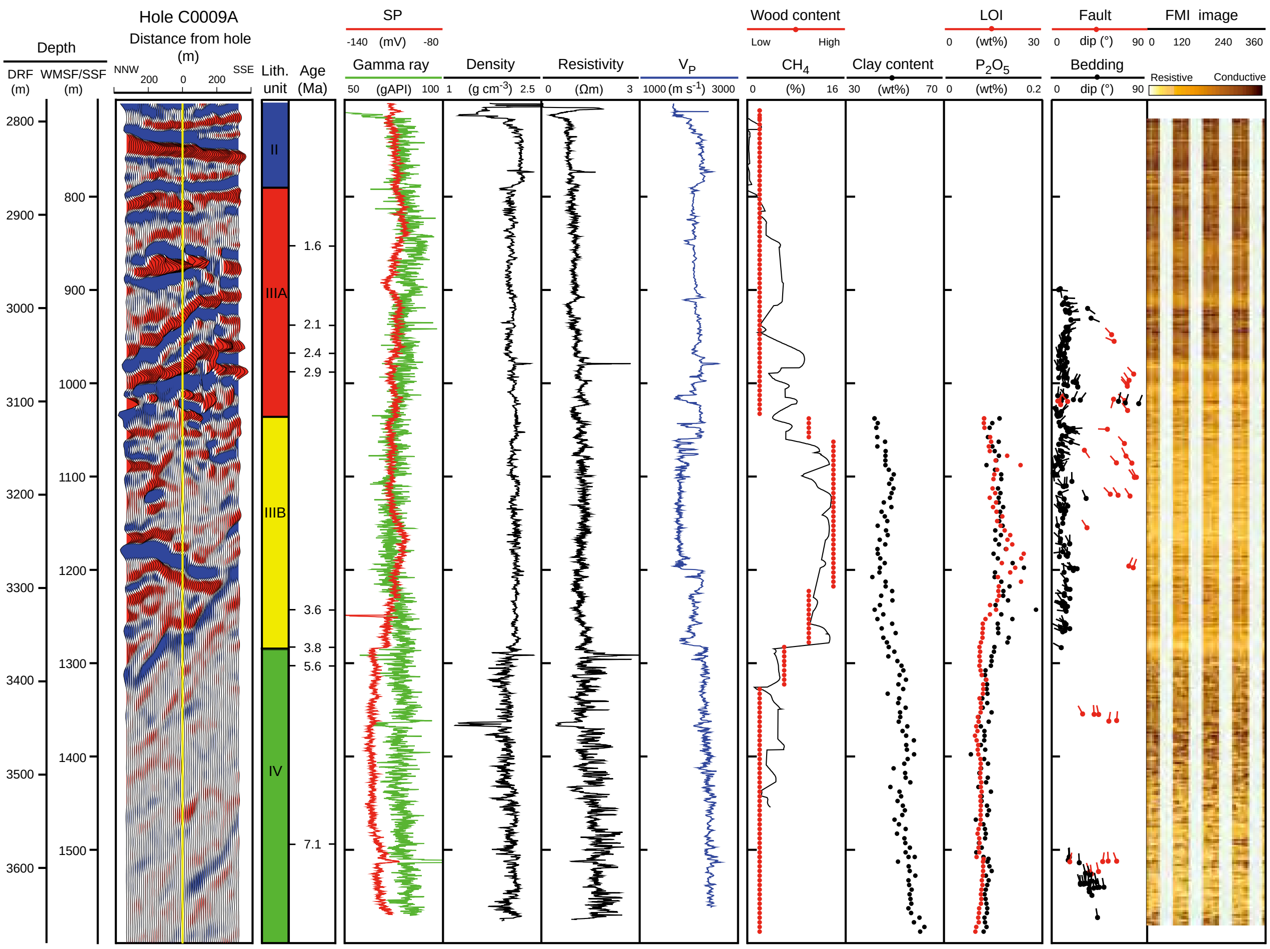


Figure 4. Site summary diagram for Site C0009 within the central forearc basin and hanging wall of the seismogenic plate boundary fault, showing wireline logs and cuttings data from ~700 mbsf to 1600 mbsf. SP=spontaneous potential, LOI=loss on ignition, FMI=Formation MicroImager (resistivity image).

by the D/V *Chikyu* (Saffer et al., 2009). Riser drilling (Fig. 3A) enabled several significant measurements new to IODP, including measurement of *in situ* stress magnitude and pore pressure using the Modular Formation Dynamics Tester (MDT) wireline tool (Fig. 3B), real-time mud gas analysis, and the analysis of drill cuttings. These types of measurements are critical for addressing the scientific objectives of the NanTroSEIZE project and will be utilized in future riser drilling operations targeting the deeper seismogenic portions of the plate boundary and megasplay fault systems. Data collected from the long offset 'walkaway' VSP experiment will allow remote imaging and resolution of properties of the deeper plate boundary fault system. The first observatory instruments of the NanTroSEIZE experiment were installed during Expedition 319, in the form of a simple instrument package (termed a "smart plug") at Site C0010, where it was designed to monitor pressure and temperature at the shallow megasplay fault (Araki et al., 2009; Saffer et al., 2009).

## Site C0009

All of the primary planned scientific objectives were achieved through successful drilling operations at this site. Riserless drilling, with gamma ray logging data, and casing to 703.9 mbsf were followed by preparations for riser drilling of the deeper hole. Prior to riser drilling, a Leak-Off Test (LOT) was conducted for operational reasons, and it provided a measurement of minimum *in situ* stress magnitude. Riser drilling continued from 703.9 to a Total Depth (TD) of 1604 mbsf. Throughout riser operations, cuttings and mud gas were collected for analysis. From a depth of 1017 mbsf, cuttings were sufficiently cohesive to allow analyses of detailed lithology, bulk composition, and some structural and physical properties, in addition to lithology and biostratigraphic analysis of incohesive cuttings at shallower depths. Limited coring at the base of the hole (1510–1594 mbsf) allowed calibration of cutting measurements and log data as well as analysis of detailed lithology, structure, physical properties, and geochemistry. Cores will also provide material for shore-based geotechnical testing that will help in the design and engineering of the planned future borehole observatory at this site. Following riser drilling, three wireline runs from ~705 mbsf to TD collected a range of datasets within the riser hole, including density, resistivity image, caliper, and gamma ray logs. Cuttings and core samples and logs together provide information about stratigraphy, age, composition, physical properties, and structure of the forearc basin sediments and underlying material (Fig. 4). The third

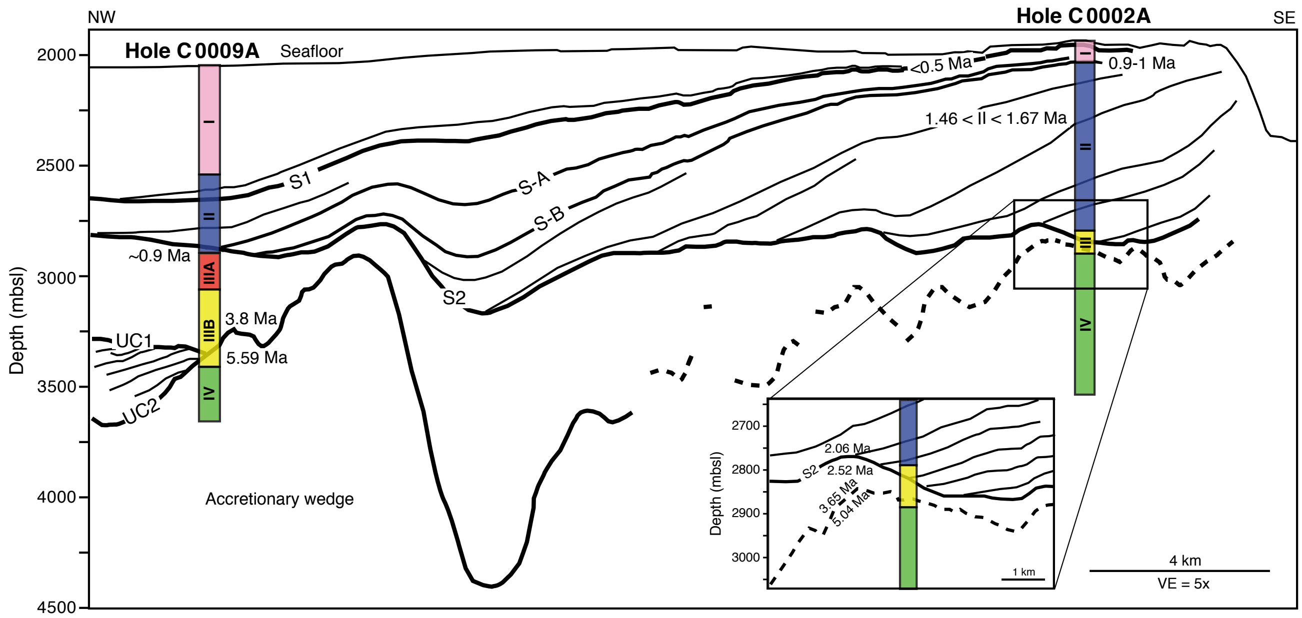


Figure 5. Interpretation of seismic line across the Kumano forearc basin including correlation between Sites C0009 (this expedition) and C0002 (Expeditions 314, 315; Kinoshita et al., 2009b) using seismic and borehole data. Lithologic units are shown at each site. Key regional seismic surfaces are also highlighted (UC1, UC2 = angular unconformities; S1, S2= regional seismic surfaces; S-A, S-B = representative correlatable surfaces within forearc basin stratigraphy). Inset shows detail of Units III-IV at Site C0002. See Saffer et al. (2009, 2010) for further details of seismic stratigraphy and structure.

wireline logging run utilized the MDT tool (Fig. 3B) to measure *in situ* stress magnitude, pore pressure, and permeability at multiple positions downhole between ~700 mbsf and 1600 mbsf. Following riser operations, the hole was cased and cemented in preparation for future observatory installation. The final operation at Site C0009 was a walkaway VSP experiment, conducted using the JAMSTEC vessel R/V *Kairei*, followed by a zero-offset VSP. For the walkaway VSP, the R/V *Kairei* fired airguns along a transect perpendicular to the margin (maximum offset 30 km) and along a circular trackline around the vessel to a wireline array of seismometers within the borehole. Airguns onboard D/V *Chikyu* were then fired and recorded on the borehole seismometer array for the zero offset VSP. These experiments together provide improved definition of velocity (and hence depth) and structure, including anisotropy, around the borehole and of the underlying plate boundary.

## Preliminary Results, Site C0009

Combining cuttings, core data, and log data, four stratigraphic units were defined (Fig. 4). Units I and II (0–791 mbsf) are Quaternary forearc basin deposits characterized by mud interbedded with silt and sand, with shallower Unit I being relatively more sand rich. Plio-Pleistocene Unit III (silty mudstone with rare silty sand interbeds) is notable for its high wood/lignite and methane content from cuttings and from analysis of formation gases released and collected in the drill mud. These are particularly concentrated in the lower subunit (IIIB), which is defined by increased organic material (from wood chips, total organic carbon (TOC) and loss on ignition (LOI) concentrations), methane, and glauconite (Fig. 4). The molecular composition of methane suggests a microbial source, consistent with estimated temperature at the bottom of the hole (~50°C) and with an interpretation of gas generated *in situ* from terrestrially sourced organic matter. A major angular unconformity documented in both cuttings and log datasets and representing a hiatus of ~1.8 Ma is crossed at 1285 mbsf and marks the Unit III-IV boundary (Fig. 4). This unconformity can be traced across the Kumano forearc basin (Fig. 5). The underlying unit (Unit IV) is composed of late Miocene silty mudstone with minor silt and vitric tuff turbiditic interbeds. All four units were deposited above the paleo CCD (at ~4000 m depth today). The stratigraphic succession is interpreted as a series of relatively fine-grained forearc basin-filling mudstones and thin turbidites (Units I, II, and/or III) underlain by older forearc basin, slope deposits or accreted prism sediments (Units IV and/or III) (see Saffer et al., 2010 for further discussion of the origin of Unit IV). As part of future research, the drilling results from Site C0009, together with results from Stage 1, can be integrated with 3-D seismic reflection data to better understand the history of forearc basin development and its potential relationship to activity on the megasplay fault.

Structural interpretations of the forearc basin and underlying slope basin-prism units were derived primarily from log and cuttings data and by comparison with cores at the base of the hole. Many types of minor structures, including faults with measurable displacement, are identified in cores. However, deformation is markedly more subdued than within the accretionary prism sediments (Unit IV) at the base of Site C0002, close to the seaward edge of the forearc basin.

Structures can also be identified and categorized in cuttings of ~2 cm or larger diameter. This technique allowed the distribution of vein structures, associated with probable tectonic-induced dewatering, to be determined downhole. Wireline log Formation MicroImager (FMI) resistivity images and caliper data were used to identify the orientation of borehole enlargement, indicating the minimum horizontal stress orientation ("borehole breakouts"). These results allowed the *in situ* stress orientation to be determined (Lin et al., 2010), complementing measurements of *in situ* stress magnitude from other tools (see below) and *in situ* stress measurements at other sites across the margin (McNeill et al., 2004; Ienaga et al., 2006; Byrne et al., 2009). Minimum horizontal stress consistently trends NE-SW downhole (~700–1600 mbsf); therefore, the maximum horizontal stress trends NW-SE (Fig. 6). This is similar to that observed in other boreholes across the accretionary prism and megasplay fault (TDs of ~400-1000 mbsf for NanTroSEIZE Stage 1 boreholes; see Kinoshita et al., 2009b), and is perpendicular to the margin and roughly parallel to the plate convergence direction (Fig. 6). This orientation, however, contrasts with that in the outer forearc basin, at Site C0002, where maximum horizontal stress is NE-SW. This Site C0002 orientation is consistent with multiple lines of evidence for margin-normal extension, potentially driven by uplift and tilting of the seaward forearc basin.

Measurements of the physical properties of sediments and rocks (bulk density, P- and S-wave velocity, resistivity, porosity, magnetic susceptibility, and thermal conductivity) were derived from wireline logs and core and cuttings materials. Cuttings materials are likely to be affected by the drilling process and the time of exposure to drilling mud; therefore, physical properties and some geochemical measurements are likely to be compromised. In particular, porosity is overestimated and bulk density underestimated. Relative bulk compositions are subject to errors due to artifacts in carbonate content associated with the interaction between cuttings and the drilling mud. However, relative downhole trends may be valid. Log-derived P-wave velocity and Poisson's ratio are markedly reduced (Fig. 4) where methane gas concentrations are high (primarily in Unit IIIB), and preliminary calculations suggest a gas saturation of ~10%. Corrected velocities from these sonic logs and from the later VSP experiment (see below) were applied to the 3-D seismic reflection data at the borehole to allow integration of borehole and seismic datasets.

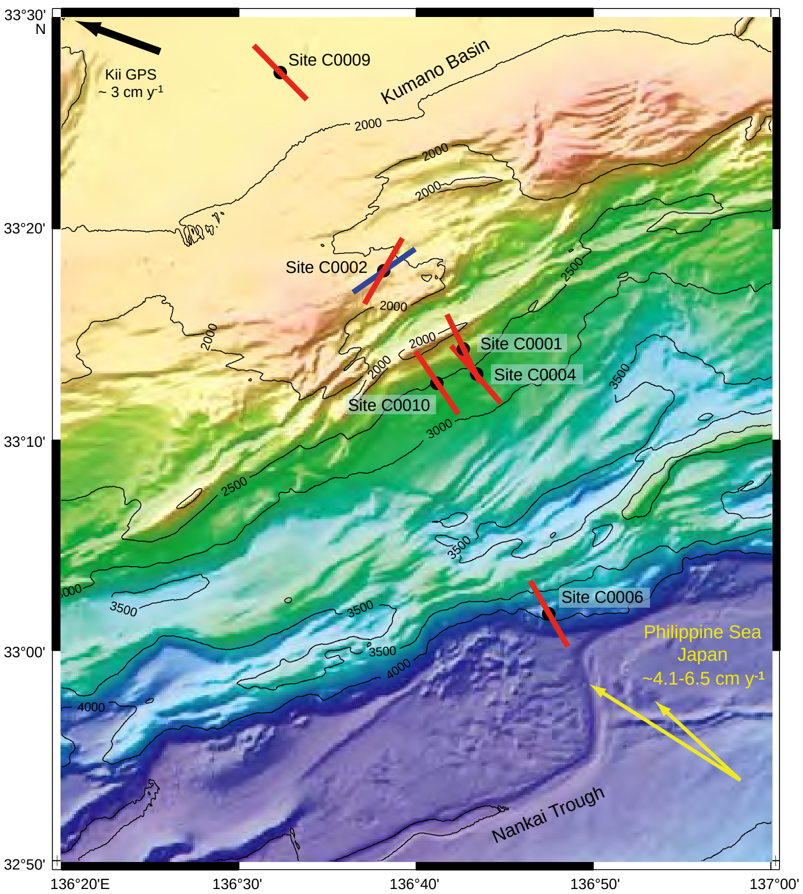


Figure 6. Map showing orientations of maximum horizontal stress inferred from borehole breakouts (see also Kinoshita et al., 2009a). At Site C0002, red line = orientation in forearc basin sediments, blue line = orientation in underlying accretionary prism. Yellow arrows indicate range of suggested convergence rates between the two plates and black arrow indicates GPS-constrained displacement on the Kii peninsula (Seno et al., 1993; Miyazaki and Heki, 2001; Heki, 2007).

A series of new downhole measurements of least principal stress magnitude ($\sigma_3$), pore pressure, and permeability were made using the MDT wireline logging tool (Fig. 3B) within the riser drilled section of the forearc basin and underlying sediments (~700–1600 mbsf). This was the first time this tool was used in ocean drilling (its diameter prevents usage in IODP non-riser holes). The tool has two components: a single probe which makes discrete measurements of pore pressure and fluid mobility; and the dual packer which isolates an interval of the borehole (set at 1 m for Expedition 319) to measure pore pressure and fluid mobility during a drawdown test and stress magnitude by hydraulic fracturing. Nine single-probe measurements, one dual packer drawdown test, and two dual packer *in situ* stress magnitude tests were conducted at Site C0009. The pore pressure measurements indicate that formation pore pressure is hydrostatic or very slightly elevated to depths of at least 1460 mbsf. Permeabilities from the single probe range from ~$10^{-16}$ $m^2$ to $10^{-14}$ $m^2$, with variations that are generally consistent with lithology. Permeability from the drawdown test within the clay-rich Unit IV yielded slightly lower permeability of $1.3x10^{-17}$ $m^2$. However, the pore pressure and permeability measurements should be viewed with some caution, as the MDT tool is typically used in more permeable formations, and a long pressure recovery time is needed in the low permeability formations drilled here. Hydraulic fracturing tests were conducted at ~870 mbsf within the forearc basin sediments, and at ~1460 mbsf near the bottom of the borehole within older forearc basin, slope deposits, or accreted sediments of the prism. The shallower test is thought to be reliable and can be compared with the leak-off test at a comparable depth (~710 mbsf). Both tests suggest that $\sigma_3$ is ~30–35 MPa and horizontal (therefore the minimum horizontal stress).

The vertical seismic profiling experiment was conducted successfully and included a walkaway and zero offset component. For the walkaway experiment, a single 53.4-km line perpendicular to the margin (880 shots) and a circular path of 3.5 km radius around the borehole (275 shots) were shot by the R/V *Kairei*. During the walkaway experiment, direct wave arrivals, refractions from the accretionary prism, and reflections from prism, megasplay fault, and plate boundary interfaces were recorded. These will provide information on seismic velocity (enabling deeper drilling targets to be determined), seismic properties, and structure of the deeper subduction zone. Anisotropy was observed during the circular transect, compatible with the *in situ* stress orientation measurements from logging results (Hino et al., 2009). The zero-offset experiment provided improved seismic velocity measurements around and immediately below the borehole, thus allowing the results from cores, cuttings, logs, and seismic data to be depth calibrated and integrated with confidence.

## Site C0010

Operations at Site C0010 included running a minimal array of MWD/LWD logging tools (gamma ray, resistivity, including resistivity image) across the shallow megasplay fault system to a TD of 555 mbsf (Fig. 7), followed by casing of the hole, an observatory dummy run with a strainmeter and seismometer to test the impact of deployment on the instruments (Fig. 3C), and installation of a simple short-term observatory package ('smart plug') to measure temperature and pressure over a period of a few years (Fig. 8), which is a crucial component of the NanTroSEIZE experiment. The MWD/LWD data allow definition of the major lithologic units and identification of the megasplay fault zone and its properties. Comparison with Site C0004 (Kinoshita et al., 2009b) reveals considerable differences in both hanging wall and fault zone properties over only ~3.5 km along strike.

### Preliminary Results, Site C0010

Three distinct lithologic units are defined at Site C0010 (Fig. 7) based on logging data and through comparison with

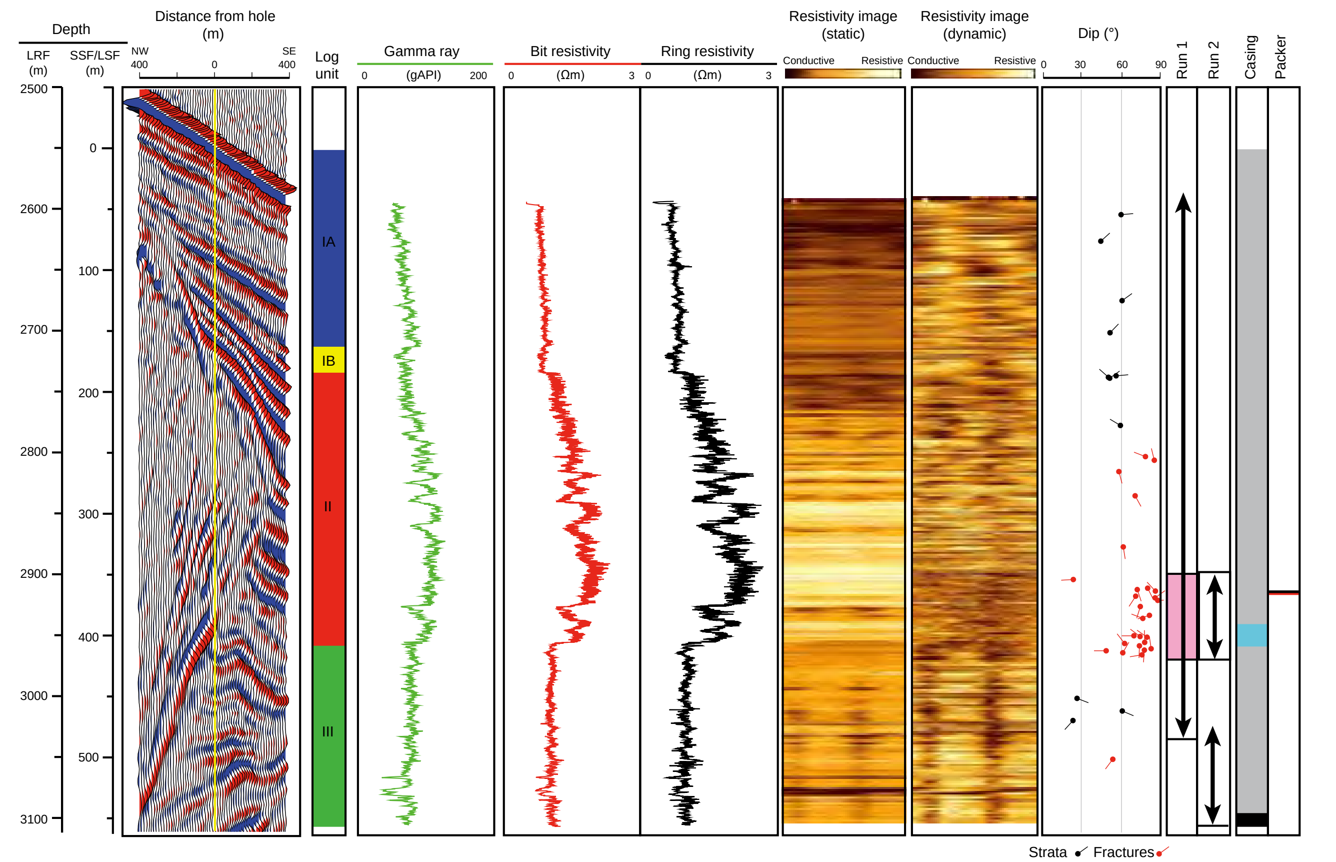


Figure 7. Site summary diagram for Site C0010 across the shallow megasplay fault zone showing LWD/MWD data. Vertical black arrows indicate sections of borehole logged during the two logging runs (section in pink reamed and relogged during logging Run 2). Key elements of casing and hole suspension for observatory instrument installation relative to the position of the fault zone are shown at right: blue = casing screens; black = casing shoe; thin black line = retrievable packer; thin red line = smart plug.

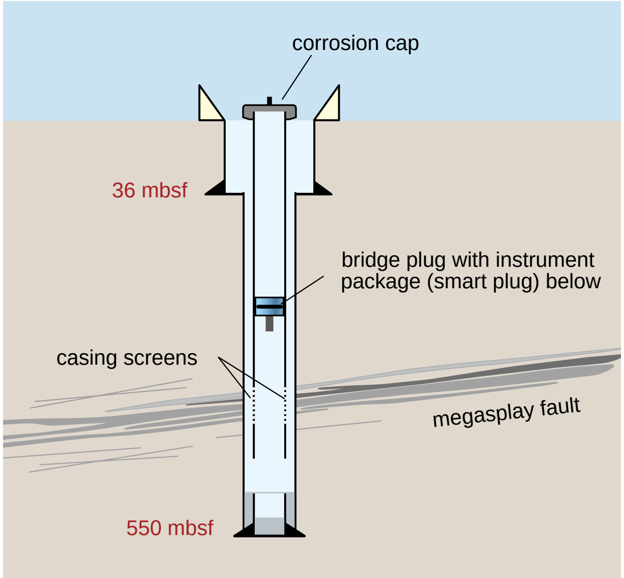

Figure 8. Diagram of smart plug observatory to monitor pressure and temperature changes within the megasplay fault zone at Site C0010.

Site C0004 (Kinoshita et al., 2009b)—slope deposits (Unit I, 0–183 mbsf); thrust wedge/hanging wall of the megasplay fault zone (Unit II, 183–407 mbsf); and overridden slope deposits/footwall of the megasplay fault zone (Unit III, 407 mbsf to TD). At Site C0010, the thrust wedge has lower gamma ray and higher resistivity values than its equivalent at Site C0004. These values suggest higher clay content and potentially increased compaction in the Site C0010 thrust wedge. Porosity estimated from resistivity log values indicates reduced porosity within the C0010 thrust wedge, although low resistivity may in part result from high clay content. Marked reductions in resistivity across the megasplay fault zone correspond to a negative (or inverted) polarity seismic reflector, suggesting reductions in velocity and density into the underthrust/overridden slope deposits of the footwall. At nearby Site C0004, the equivalent reflector is positive polarity, emphasizing that differences in properties, primarily of the hanging wall thrust wedge, can occur over a very short distance within the forearc. These differences may originate from contrasts in original composition or in degree of exhumation along the thrust fault.

Ship heave during logging resulted in variable quality of resistivity image data for structural interpretation; however, analysis of orientations of borehole breakouts revealed an orientation of horizontal maximum stress of NW-SE (Fig. 6). This orientation is similar to that measured at other sites across the prism during NanTroSEIZE Stage 1 and similar to the orientation at Site C0009 in the central forearc basin. An abrupt downhole change in breakout orientation across the megasplay fault zone at Site C0010 is consistent with a sharp mechanical discontinuity at the fault zone (Barton and Zoback, 1994); such a change is not observed at nearby Site C0004, where the megasplay is defined as a broad ~50-m-thick fault-bounded package. Minor faults are concentrated around the thrust zone, as might be expected.

Two sensor dummy runs were conducted using a strainmeter, seismometer, temperature loggers, and an accelerometer-tiltmeter (Fig. 3C) to test the degree of vibration and shock associated with running the instrument package through the water column and reentering the borehole. Unfortunately, during the first run the seismometer and strainmeter became detached and lost due to strong vibrations of the drill pipe in a high current velocity area; however, acceleration, tilt, and temperature data were recorded within the water column. The second run (including a dummy strainmeter with identical dimensions) attempted to test reentry conditions at the wellhead. During both runs, vibrations in the water column resulting from high current velocity were significantly greater than expected, and these results will be critical for modifying future installations of observatory instruments. On a more positive note, a temporary single observatory "smart plug" was successfully installed in the borehole. Screened casing intervals and a retrievable packer will isolate the megasplay fault zone (Figs. 7 and 8) and allow measurements of pressure (referenced to hydrostatic pressure) and temperature to be taken regularly at one-minute intervals over a period of a few years before the instrument package is recovered during future NanTroSEIZE operations.

## Key Scientific and Technical Results and Future Work

Data from Expedition 319 and previous NanTroSEIZE drill sites can now be integrated to provide constraints on present-day stress orientation and magnitude across the forearc; they can also be compared with past records of deformation at a range of scales (from core to seismic), incorporating, for the first time, measurements of *in situ* stress magnitude. The emerging picture of stress conditions (Kinoshita et al., 2009a and 2009b; Tobin et al., 2009) is one in which maximum horizontal stress is slightly oblique to the plate convergence across the prism and the inner forearc basin, but deviates from this trend in the outer forearc basin where margin perpendicular extension dominates (Fig. 6). *In situ* stress magnitude at Site C0009 suggests that a normal or strike-slip faulting regime dominates today. Normal faults are observed in reflection data of nearby parts of the basin, but fault orientations from resistivity images are inconsistent with these present-day stress measurements and likely represent an earlier phase of deformation and evolution of stress regimes in the hanging wall of the plate boundary fault.

For the first time, *in situ* hydrological properties of sediments and rocks have been obtained for scientific analysis. These properties (e.g., formation pore pressure and permeability) are critical parameters for understanding the role of fluids in deformation of the forearc and will ultimately be important for determining the role of fluids in fault development and in seismogenic behavior. Properties and behavior can be inferred from core samples and logs, but only direct measurements at depth provide *in situ* properties where these processes are taking place.

Performing riser drilling for the first time in IODP presented a range of operational and analytical challenges. Experiences from this expedition will be valuable for future riser drilling operations within scientific ocean drilling. New methods of analyzing cuttings were developed, and the validity of specific measurements on cuttings was tested. Methods of integrating cores, cuttings data, and log data were also developed to provide the most scientifically realistic interpretation of downhole geological (including lithology, biostratigraphy, structure) and physical properties, particularly important for future deep boreholes where continuous coring will not be feasible. Existing methods for drill mud gas analysis established for continental drilling were also applied successfully to drilling in a marine environment.

Future work will focus on the following: a) results made possible by these new techniques, b) continued post-expedition shore-based laboratory and analytical study of samples, and c) integration of the drilling results from Expedition 319 with existing results across the broader forearc from NanTroSEIZE Stage 1 and with non-drilling datasets, such as 3-D seismic reflection data. Collectively, these will provide the context of regional forearc structure including that of the deeper seismogenic plate boundary.

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# IODP Expedition 322 Drills Two Sites to Document Inputs to The Nankai Trough Subduction Zone

by Michael B. Underwood, Saneatsu Saito, Yu'suke Kubo, and the IODP Expedition 322 Scientists

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## Abstract

The primary goals during Expedition 322 of the Integrated Ocean Drilling Program were to sample and log the incoming sedimentary strata and uppermost igneous basement of the Shikoku Basin, seaward of the Nankai Trough (southwestern Japan). Characterization of these subduction inputs is one piece of the overall science plan for the Nankai Trough Seismogenic Zone Experiment. Before we can assess how various material properties evolve down the dip of the plate interface, and potentially change the fault's behavior from stable sliding to seismogenic slip, we must determine the initial pre-subduction conditions. Two sites were drilled seaward of the trench to demonstrate how facies character and sedimentation rates responded to bathymetric architecture. Site C0011 is located on the northwest flank of a prominent basement high (Kashinosaki Knoll), and Site C0012 is located near the crest of the seamount. Even though significant gaps remain in the coring record, and attempts to recover wireline logs at Site C0012 failed, correlations can be made between stratigraphic units at the two sites. Sedimentation rates slowed down throughout the condensed section above the basement high, but the seafloor relief was never high enough during the basin's evolution to prevent the accumulation of sandy turbidites near the crest of the seamount. We discovered a new stratigraphic unit, the middle Shikoku Basin facies, which is typified by late Miocene volcaniclastic turbidites. The sediment-basalt contact was recovered intact at Site C0012, giving a minimum basement age of 18.9 Ma. Samples of interstitial water show a familiar freshening trend with depth at Site C0011, but chlorinity values at Site C0012 increase above the values for seawater toward the basement contact. The geochemical trends at Site C0012 are probably a response to hydration reactions in the volcaniclastic sediment and diffusional

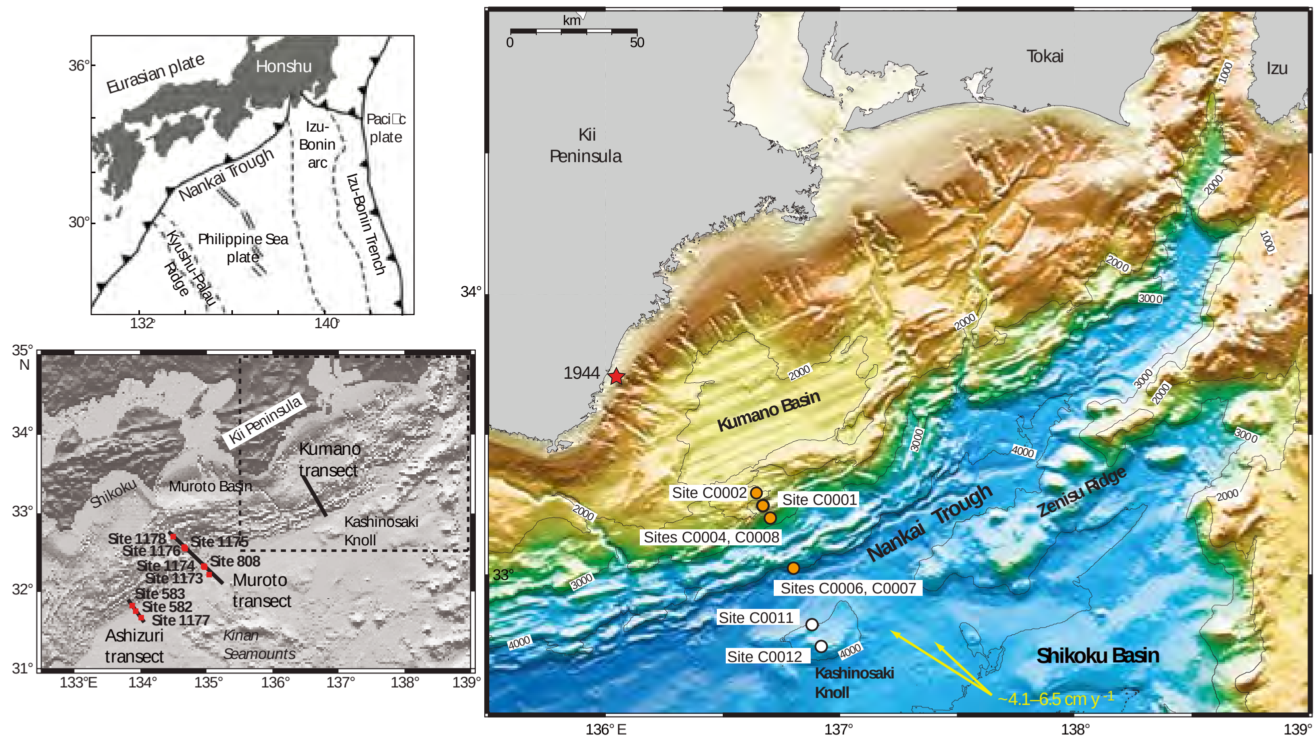


Figure 1. Maps of Nankai Trough and Shikoku Basin showing locations of previous DSDP and ODP drill sites (Ashizuri and Muroto transects), Kumano transect area, Stage 1 NanTroSEIZE coring sites (C0001, C0002, C0004, C0006, C0007, C0008), and Expedition 322 drill sites (C0011 and C0012). Yellow arrows show convergence vector between Philippine Sea plate and Japanese Islands (Eurasian plate). Red star gives epicenter for nucleation of large subduction earthquake in 1944.

exchange with seawater-like fluid in the upper igneous basement. These data are important because they finally establish an authentic geochemical reference site for Nankai Trough, unaffected by dehydration reactions, and they provide evidence for active fluid flow within the upper igneous crust. Having two sets of geochemical profiles also shows a lack of hydrogeological connectivity between the flank and the crest of the Kashinosaki Knoll.

## Introduction and Goals

Subduction megathrusts are responsible for some of the world's deadliest earthquakes and tsunamis. To improve our understanding of these hazards, an ambitious project known as the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) was initiated along the subduction boundary of southwestern Japan, with the overarching goal of creating a distributed observatory spanning the up-dip limit of seismogenic and tsunamigenic behavior (Tobin and Kinoshita, 2006a, 2006b). Using an array of boreholes across the Kumano transect area (Fig. 1), scientists hope to monitor *in situ* conditions near a major out-of-sequence thrust (megasplay) and the subduction megathrust (plate interface). This multi-stage project is in the process of documenting several key components of the subduction margin, starting with the pre-subduction inputs of sediment and oceanic basement (Underwood et al., 2009), moving landward into the shallow plate interface (Tobin et al., 2009), and finally drilling to depths of 6–7 km where earthquakes occur.

Expedition 322 of the Integrated Ocean Drilling Program (IODP) was organized to sample and log incoming sedimentary strata and igneous basement of the Shikoku Basin, prior to their arrival and burial at the Nankai subduction front (Saito et al., 2009). It is only through such sampling that we can pinpoint how various geologic properties and diagenetic transformations (e.g., clay composition, cementation, microfabric, fluid production, pore pressure, friction, thermal state) change in 3-D space and through time. When viewed in the broader context of NanTroSEIZE, it is particularly important to understand pre-subduction conditions, because the down-dip evolution of those initial properties is what ultimately changes slip behavior along the plate interface from aseismic to seismic (Vrolijk, 1990; Hyndman et al., 1997; Moore and Saffer, 2001). Drilling was therefore conducted at two sites seaward of the trench (Fig. 1). Site C0011 is located on the northwest flank of a prominent bathymetric high (the Kashinosaki Knoll), whereas Site C0012 is located near the crest of the seamount.

## Geological Setting and Earlier Work

The Shikoku Basin formed as part of the Philippine Sea plate during the early to middle Miocene by rifting and seafloor spreading along the backarc side of the Izu-Bonin volcanic chain (Okino et al., 1994; Kobayashi et al., 1995). Prominent basement highs within the Shikoku Basin include the Kinan seamount chain (Fig. 1), which grew along the axis of the extinct backarc spreading center, and isolated seamounts such as the Kashinosaki Knoll (Ike et al., 2008a). The subducting plate is currently moving toward the northwest beneath the Eurasian plate at a rate of ~4 to 6 cm $yr^{-1}$ (Seno et al., 1993; Miyazaki and Heki, 2001), roughly orthogonal to the axis of the Nankai Trough. Shikoku Basin deposits, together with the overlying Quaternary trench wedge, are actively accreting at the deformation front, as demonstrated within the Kumano transect area by IODP Expeditions 314, 315, and 316 (Tobin et al., 2009).

As summarized by Underwood (2007), our knowledge of inputs to the Nankai subduction zone is rooted in pioneering drilling discoveries from the Muroto and Ashizuri transects (Deep Sea Drilling Project [DSDP] Legs 31 and 87 and Ocean Drilling Program [ODP] Legs 131, 190, and 196) (Karig et al., 1975; Kagami et al., 1986; Taira et al., 1991; Moore et al., 2001a; Mikada et al., 2002). Those studies demonstrated, among other things, that the plate-boundary fault (décollement) propagates through Miocene strata of the lower Shikoku Basin facies, at least near the toe of the accretionary prism (Taira et al., 1992; Moore et al., 2001b). One of the primary objectives of NanTroSEIZE is to track physical/chemical changes down the plate interface from shallow depths toward seismogenic depths, so the highest-priority sampling targets lie within the lower Shikoku Basin.

Seismic reflection data from across the width of the Shikoku Basin reveal a large amount of heterogeneity in terms of acoustic character and stratigraphic thickness (Ike et al., 2008a, 2008b). Seafloor relief was created during construction of the underlying igneous basement, and that relief strongly influenced the basin's early depositional history (Moore et al., 2001b; Underwood, 2007). As an example of such influence, elevation of the seafloor along the Kinan seamount chain inhibited transport and deposition of sand by gravity flows, so Miocene–Pliocene sediments above the extinct ridge consist almost entirely of hemipelagic mudstone. In contrast, coeval Miocene strata on the flanks of the Kinan basement high consist largely of sand-rich turbidites (Moore et al., 2001b). There are also important differences across the width of the basin (from SW to NE) in values of heat flow, clay mineral assemblages, and the progress of clay-mineral diagenesis (Yamano et al., 2003; Underwood, 2007; Saffer et al., 2008).

Within the Kumano transect area (Fig. 1), seismic reflection data show that the décollement is hosted by lower Shikoku Basin strata to a distance of at least 25–35 km landward of the trench (Moore et al., 2009). Farther landward, the plate-boundary fault steps down section to a position at or near the interface between sedimentary rock and igneous basement (Park et al., 2002). To learn more about the stratigraphic architecture of the Shikoku Basin, Expedition 322 drilled Site C0012 at the crest of Kashinosaki Knoll and Site

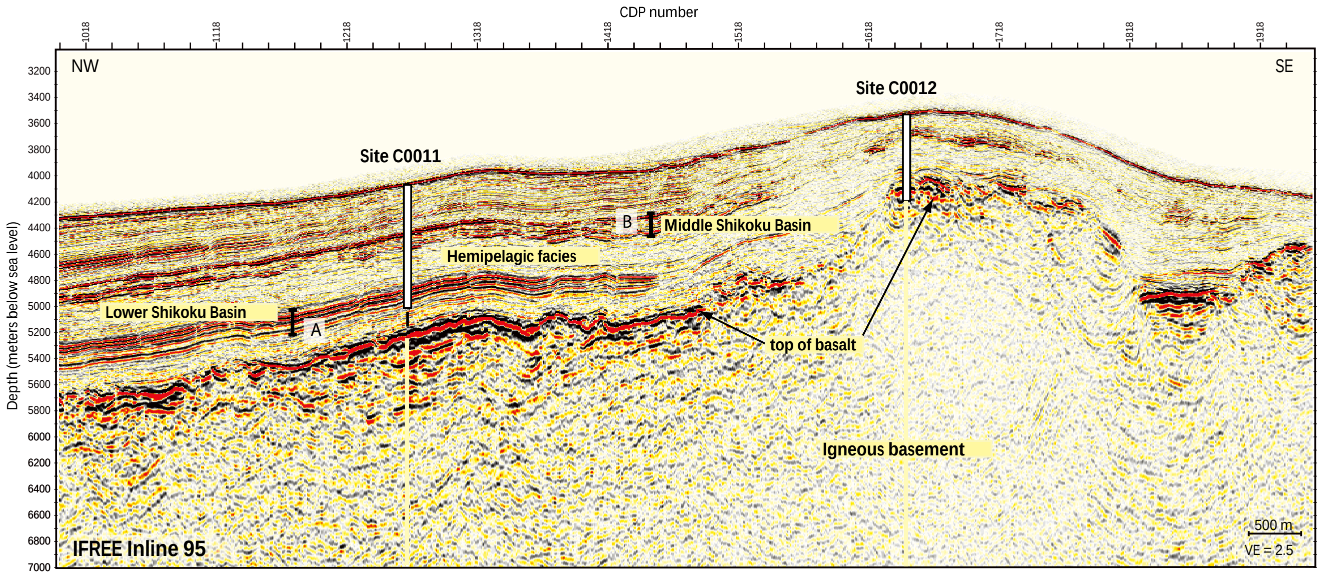


Figure 2. Portion of IFREE 3-D seismic reflection Line 95 showing Sites C0011 and C0012. Depth section corrected during Expedition 322 after adjustments to velocity model following acquisition of LWD data at Site C0011. VE = vertical exaggeration, I marks distinctive intervals of high amplitude reflectors ([A] at ~700 mbsf to ~900 mbsf and [B] at ~350 mbsf to ~500 mbsf at the location of Site C0011).

C0011 along its northwest flank (Fig. 2). In the vicinity of Site C0011, seismic profiles include two particularly distinctive intervals of high-amplitude reflectors: the first from ~350 meters below seafloor (mbsf) to ~500 mbsf and a second with better lateral continuity of reflectors beginning at ~700 mbsf (Fig. 2). Both of these packets of reflectors change thickness but can be traced up and over the crest of Kashinosaki Knoll. These particular depth intervals, plus the sediment-basalt interface, represented the primary coring targets for the expedition (Saito et al., 2009).

## Principal Results from Site C0011

Near the end of Expedition 319, measurement-while-drilling and logging-while-drilling (LWD) data were collected at Hole C0011A (Saffer et al., 2009). Generally, we were able to make confident correlations between the logs and subsequent data from rotary core barrel (RCB) cores, with a vertical offset of ~4 m between the coring hole and the logging hole. Five logging units were defined on the basis of visual inspection of the gamma ray and ring resistivity responses (Underwood et al., 2009). These subdivisions also correlate reasonably well with the seismic stratigraphy. For example, the two intervals with high amplitude reflectors (Fig. 2) match up with log responses that are indicative of sand (stone) and volcanic ash/tuff beds. Structural analysis of the borehole resistivity images showed that bedding dips <20° toward the north, which is consistent with the relatively gentle dip observed in the seismic profiles down the landward-facing slope of Kashinosaki Knoll. Analysis of borehole breakouts indicates that the maximum horizontal stress field (SHmax) is orientated north-northeast to south-southwest, roughly perpendicular to the convergence direction of the Philippine Sea plate.

Because of contingency time restrictions (including anticipation of time lost for typhoon evacuations), coring at Hole C0011B began at 340 mbsf rather than the mudline (Fig. 3). Lithologic Unit I was not cored, so its character is inferred from LWD data (Underwood et al., 2009) and by analogy with the upper part of the Shikoku Basin at ODP Sites 808, 1173, 1174, and 1177 (Taira et al., 1992; Moore et al., 2001b). The dominant lithology of this upper Shikoku Basin facies is hemipelagic mud (silty clay to clayey silt) with thin interbeds of volcanic ash (mostly air-fall tephra). Below 340 mbsf, we used biostratigraphic data to merge certain parts of the magnetic polarity interval with the geomagnetic polar-ity reversal time-scale; this resulted in an integrated age-depth model that extends from ~7.6 Ma to ~14.0 Ma (Fig. 4). The composite model yields average rates of sedimentation (uncorrected for either compaction or rapid event deposition by gravity flows) ranging from 4.0 cm k.y.$^{-1}$ to 9.5 cm k.y.$^{-1}$.

Lithologic Unit II is late Miocene (~7.6–9.1 Ma) in age and extends in depth from 340 to 479 mbsf (Fig. 3). We named this unit the middle Shikoku Basin facies; it consists of moder-ately lithified bioturbated silty claystone with interbeds of tuffaceous sandstone, volcaniclastic sandstone, dark gray clayey siltstone without appreciable bioturbation (mud turbidites), and a chaotic interval of intermixed volcaniclastic sandstone and bioturbated silty claystone (mass transport deposit). Channel-like sand-body geometry is evident in both LWD data and seismic character. The volcanic-rich sandstones contain mixtures of primary eruptive products (e.g., fresh volcanic glass shards) and reworked fragments of pyroclastic and sedimentary deposits. The closest volcanic terrain at the time was probably the Izu-Bonin arc, located along the northeast margin of the Shikoku Basin (Taylor, 1992; Cambray et al., 1995); we interpret Izu-Bonin to be the main sediment source for SW-directed, channelized turbidity currents. No such deposits are known to exist within the western half of the Shikoku Basin.

Lithologic Unit III is middle to late Miocene (~9.1–~12.2 Ma) in age and extends from 479mbsf to 674 mbsf (Fig. 3). Its dominant lithology is bioturbated silty claystone, typical of the hemipelagic deposits throughout the Shikoku Basin. Secondary lithologies include sporadic dark gray silty claystone, lime mudstone, and very thin beds of ochre calcareous claystone. The most unusual aspect of this unit is the deceleration in the rate of hemipelagic sedimentation at ~10.8 Ma (Fig. 4).

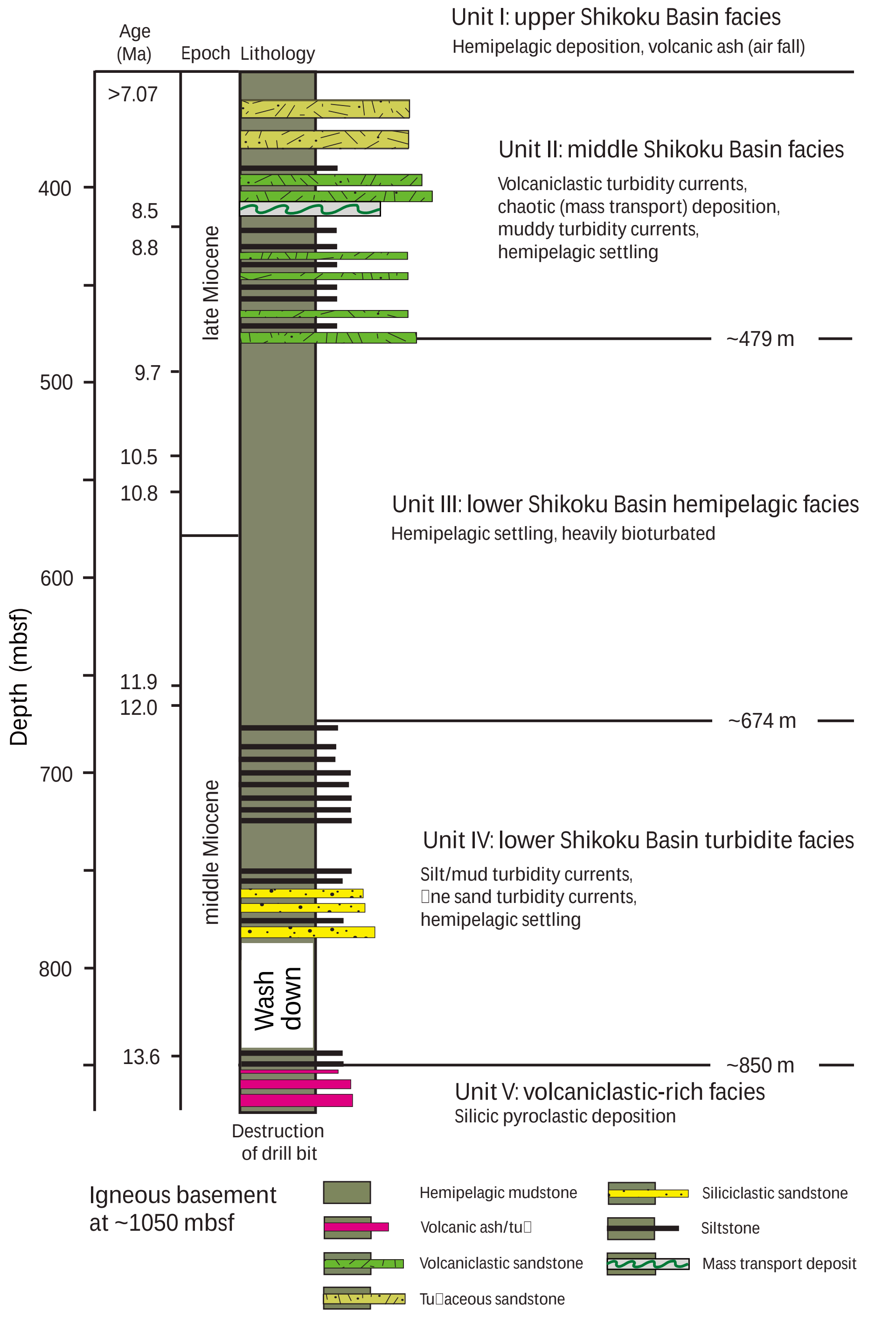

Figure 3. Lithologic units and depositional ages from nannofossils data Hole C0011B.

Unit IV is middle Miocene (~12.2–14.0 Ma) in age and extends from 674 mbsf to 850 mbsf (Fig. 3). Core recovery within this interval was particularly poor, and our interpretations were further hampered by poor core quality and the decision to wash down without coring from 782mbsf to 844 mbsf. The dominant lithology is bioturbated silty claystone with abundant interbeds of dark gray clayey siltstone (deposited by muddy turbidity currents) and fine-grained siliciclastic sandstone (deposited by sandy turbidity currents). We suggest that the most likely terrigenous sources for this sandy detritus were rock units now exposed across the Outer Zone of southwest Japan, including the Shimanto Belt (Taira et al., 1989; Nakajima, 1997). Superficially similar sand deposits, with overlapping ages, have been documented on the southwest side of the Shikoku Basin at ODP Site 1177 and DSDP Site 297 offshore the Ashizuri Peninsula of Shikoku (Marsaglia et al., 1992; Fergusson, 2003; Underwood and Fergusson, 2005).

The age of Unit V is poorly constrained within the range of middle Miocene (~14.0 Ma). It extends from 850 mbsf to 876 mbsf, but our ability to characterize these strata was prevented by poor core recovery. In fact, the unit's lower boundary coin-cides with destruction of the drill bit, which forced us to abandon the hole. The dominant lithologies are tuffaceous silty claystone and light gray tuff with minor occurrences of tuffaceous sandy siltstone. X-ray diffraction data show an abundance of smectite and zeolites within this unit as alteration products of volcanic glass. These deposits probably correlate with the thick rhyolitic tuffs at ODP Site 808 (Muroto transect of the Nankai Trough), which yielded an age of ~13.6 Ma (Taira et al., 1991).

Structural features at Site C0011 include sub-horizontal to gently dipping bedding planes and small faults. Synsedimentary creep and layer-parallel faults developed in Units II and III, whereas a high-angle normal fault/fracture system is pervasive in Units IV and V. Deformation-fluid interactions were also deduced from mineral-filled veins precipitated along faults. Poles to these structures are distributed along a north-northwest to south-southeast trend, perpendicular to the present trench axis, and the orientations correlate nicely with the LWD-based measurements.

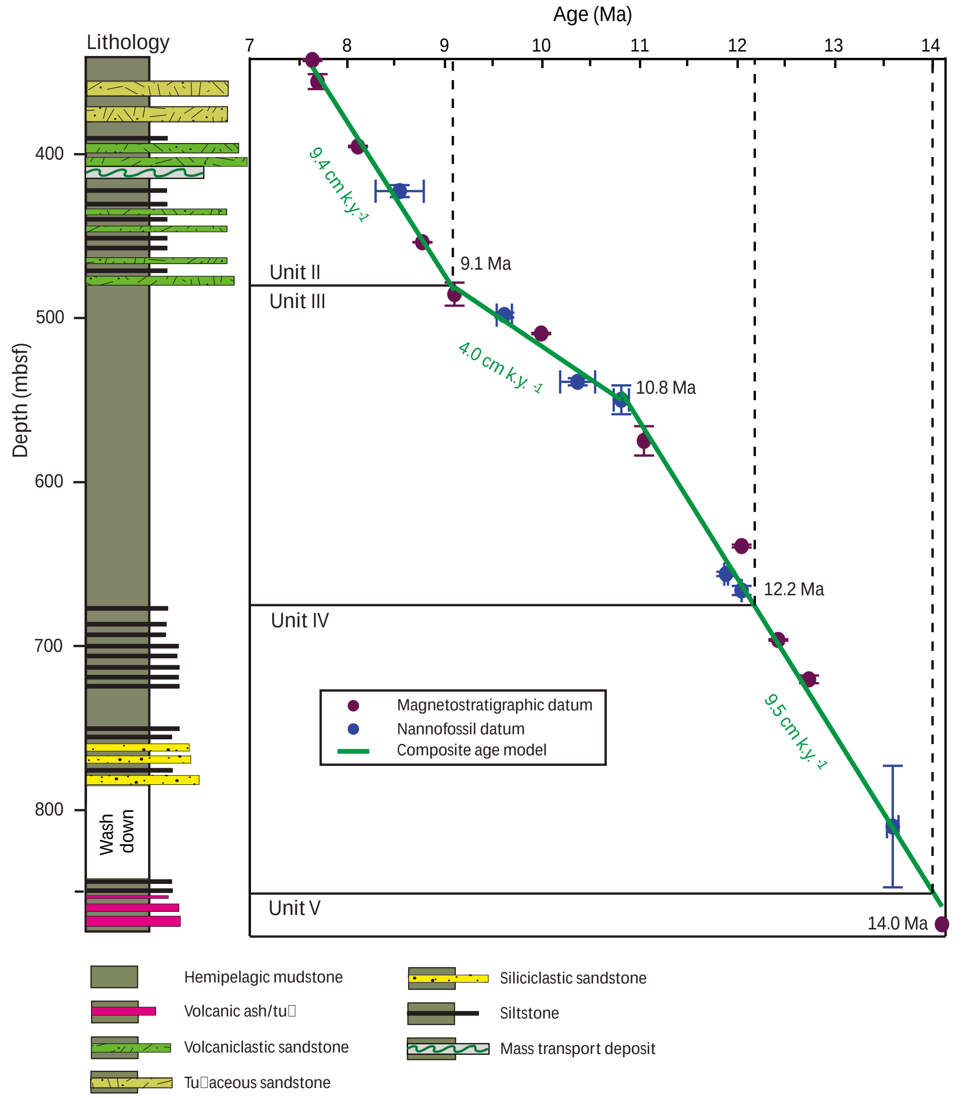


Figure 4. Integrated age-depth model for Hole C0011B using constraints from biostratigraphy and magnetostratigraphy.

Although the data are adversely affected by widespread damage to cores, physical properties show downhole increases in bulk density and decreases in porosity indicative of sediment consolidation. These trends coincide with increases in P-wave velocity and electrical resistivity. The velocity-porosity relation is consistent with previous observations from Shikoku Basin sediments (Hoffman and Tobin, 2004). Velocity anisotropy changes from isotropic to anisotropic (i.e., horizontal velocity faster than vertical velocity) near 440 mbsf, which we attribute to compaction-induced alignment of mineral grains. We also detected a shift in magnetic susceptibility near 575 mbsf, which correlates with the change in sedimentation rate at 10.8 Ma (Fig. 4).

Good quality samples were difficult to collect for interstitial water analysis because of persistent core disturbance and low water content. Contamination by seawater (drilling fluid) is evident in all data profiles, and corrections had to be made on the basis of sulfide concentrations. The top of the sampled sediment section (340 mbsf) lies beneath the sulfate-methane interface; thus, we have no information on shallow processes associated with organic carbon diagenesis. Chlorinity in the sampled fluids decreases from ~560 mM to ~510 mM, which is ~9% less than the typical value of 558 mM for seawater (Fig. 5). This freshening trend is superficially consistent with the pattern observed at ODP Site 1177, Ashizuri transect of the Nankai Trough (Moore et al., 2001a). Judging from the similarity of chlorinity profiles, we tentatively suggest that the sampled fluids were altered at greater depths by clay dehydration reactions. If this interpretation is correct, then fluid migration toward Site C0011—from zones of diagenesis in the frontal accretionary prism and/or beneath the trench wedge—probably occurred along permeable conduits of turbidite sandstone. The lack of borehole temperature measurements at Site C0011 hinders a more definitive interpretation (i.e., in situ dehydration versus deeper seated dehydration). The distributions of major and minor cations document extensive alteration of volcanogenic sediments and oceanic basement, including the formation of zeolites and smectite-group clay minerals. These reactions lead to consumption of silica, potassium, and magnesium and the production of calcium. The very high calcium concentrations (>50 mM) favor authigenic carbonate formation, even at alkalinity of <2 mM.

In spite of the sediment's low content of organic carbon (average 0.31 ± 0.17 wt%), the dissolved hydrocarbon gas concentrations in interstitial water increase with depth. Methane is present as a dis-solved phase in all samples. Ethane was detected in all but one core taken from depths >422 mbsf. Dissolved propane was first observed at 568 mbsf and is present in almost all deeper cores. Butane occurs sporadically below 678 mbsf. The widespread occurrence of ethane results in low C1/C2 ratios (~277 ± 75), which are unusual for sediments with organic carbon contents of <0.5 wt%. Without better con-straints on temperature at depth, it is difficult to resolve the potential contributions of heavier hydrocarbons from in situ production versus a deeper/hotter source coupled with up-dip migration along sandy intervals with higher permeability.

## Principal Results from Site C0012

Attempts to acquire wireline logs failed at Site C0012, so our results are based on RCB coring. During the RCB jet-in, lithologic Unit I (upper Shikoku Basin facies) was not cored between 0.81 mbsf and 60 mbsf. The unit extends from the seafloor to ~151 mbsf, below which we recovered the first volcaniclastic sandstone of middle Shikoku Basin facies (Fig. 6). The dominant lithology of Unit I is green-gray intensely bioturbated silty clay(stone), and thin layers of volcanic ash are scattered throughout. Modest amounts of biogenic calcite are compatible with hemipelagic settling on top of Kashinosaki Knoll at a water depth close to (but above) the calcite compensation depth. The integrated age-depth model (Fig. 7) places the lower boundary of Unit I at ~7.8 Ma and shows sedimentation rates decelerating from 4.3 cm k.y.$^{-1}$ to 1.2 cm k.y.$^{-1}$ at ~7.1 Ma.

Lithologic Unit II (middle Shikoku Basin facies) is late Miocene (7.8 Ma to ~9.4 Ma) in age and extends from 151 mbsf to 220 mbsf (Fig. 6). The dominant lithology recovered is green-gray silty claystone, alternating with medium- to thick-bedded tuffaceous/volcaniclastic sandstone and dark gray clayey siltstone. Unit II also contains two chaotic deposits with disaggregated pieces of volcanic-rich sandstone and mudstone that show folding, thinning, and attenuation of primary bedd-ing, probably deformed by gravitational sliding on the north-facing slope of the Kashinosaki Knoll. The volcanic sandstones were not expected at the top of the knoll, and they probably shared a common Izu-Bonin source with Unit II at Site C0011. Their existence seemingly requires upslope transfer by turbidity currents (Muck and Underwood, 1990) and/or post-depositional uplift of the basement high. Seismic data show that the facies thins toward the basement high but drapes over the crest and continues onto the seaward-facing flank (Fig. 2).

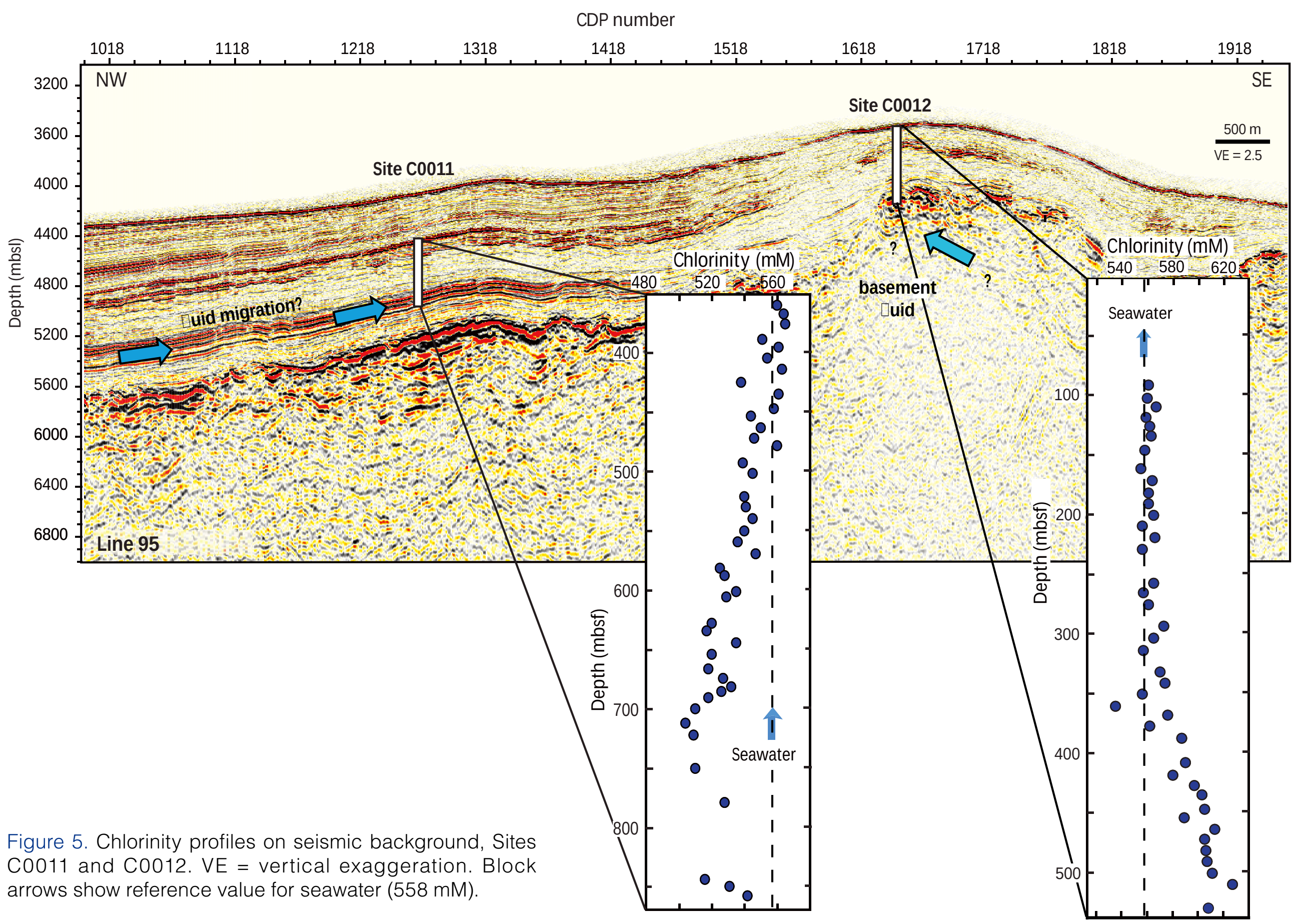


Figure 5. Chlorinity profiles on seismic background, Sites C0011 and C0012. VE = vertical exaggeration. Block arrows show reference value for seawater (558 mM).

Unit III (lower Shikoku Basin hemipelagic facies) is middle Miocene (9.4 Ma to ~12.7 Ma) in age and extends from 220 mbsf to 332 mbsf (Fig. 6). The lithology is dominated by bioturbated silty claystone, with scattered carbonate beds and clay-rich layers (possible bentonites). The upper portion of Unit III contains an interval with steeply inclined (40°–45°) bedding. From seismic data, this zone of disruption appears to be associated with rotational normal faulting. We also see evidence from nannofossils of a hiatus near the top of this deformed interval (Fig. 7). Rates of hemipelagic sedimenta-tion changed at ~12 Ma, although the magnitude of this shift is far more subtle than the effect at Site C0011 (Fig. 4).

Lithologic Unit IV (lower Shikoku Basin turbidite facies) is middle Miocene (12.7–13.5 Ma) in age and extends from 332 mbsf to 416 mbsf (Fig. 6). This interval is characterized by alternations of silty claystone, clayey siltstone, and thin, normally graded siltstone turbi-dites. Prior to drilling, we had expected this turbidite facies to pinch out against the basement high (Saito et al., 2009). The transition down-section into Unit V is not sharp (based on coarser-grained, volcaniclastic sandstone). These volcaniclastic-rich deposits range in age from early to middle Miocene (13.5 Ma to ≥18.9 Ma) and extend in depth from 416 mbsf to 528.5 mbsf. Unit V also includes beds of siltstone, siliciclastic sandstone, and tuff. Some of the sandstones display spectacular cross-laminae, plane-parallel laminae, convolute laminae, and soft-sediment sheath folds. Two detrital sources are evident for the sand grains: a volcanic terrain with fresh volcanic glass together with relatively large amounts of feldspar, and a siliciclastic source enriched in sedimentary lithic grains, quartz, and heavy minerals (including pyroxene, zircon, and amphibole). This compositional heterogeneity is reminiscent of the volcaniclastic-rich facies at ODP Site 1177 (Moore et al., 2001a). Nannofossils also provide evidence for a significant unconformity within Unit V at ~510 mbsf; the associated hiatus spans approximately 4 m.y. (Fig. 7). This unconformity may have been caused by mass wasting during early stages of turbidite sedimentation on Kashinosaki Knoll. Additional support for this interpretation comes from the chaotic and discontinuous seismic reflectors just

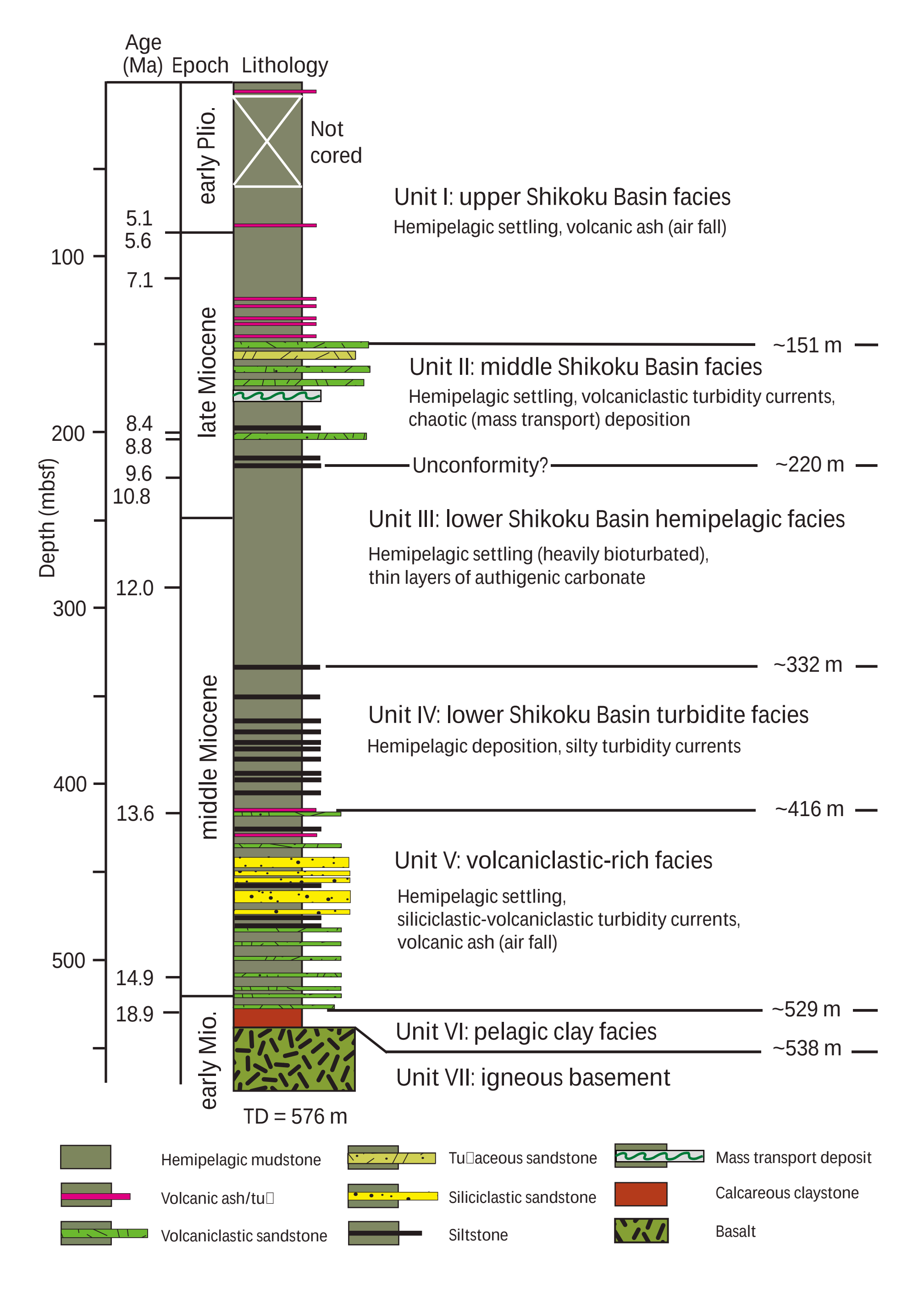


Figure 6. Lithologic units and depositional ages from nannofossils data, Hole C0012A.

below the crest of the basement high on its landward-facing flank (Fig. 2).

We succeeded in recovering the depositional contact between pelagic claystone (Unit VI) and igneous basement (Unit VII) at a depth of 537.8 mbsf (Fig. 6). The age of Unit VI is early Miocene (>18.921 Ma, with a lower limit of 20.393 Ma for the age-constraining nannofossil zone). These thin pelagic deposits are only 9.3 m thick, and they include variegated red, reddish brown, and green calcareous claystone, rich in nannofossils, with minor amounts of radiolarian spines. Carbonate content is ~20 wt%. The cored interval for the underlying basalt extends to 560.74 mbsf. Four types of lava morphology were distinguished: pillow lava, 'massive' basalt, breccia, and mixed rubble pieces caused by drilling disturbance. The basalts are aphanitic to porphyritic, and abundance of phenocrysts is highly variable, from slightly to highly phyric textures. Vesicularity is highly heterogeneous, and alteration of the basalt ranges from moderate to very high. Secondary minerals include saponite, zeolite, celadonite, pyrite, iddingsite, quartz, and calcite.

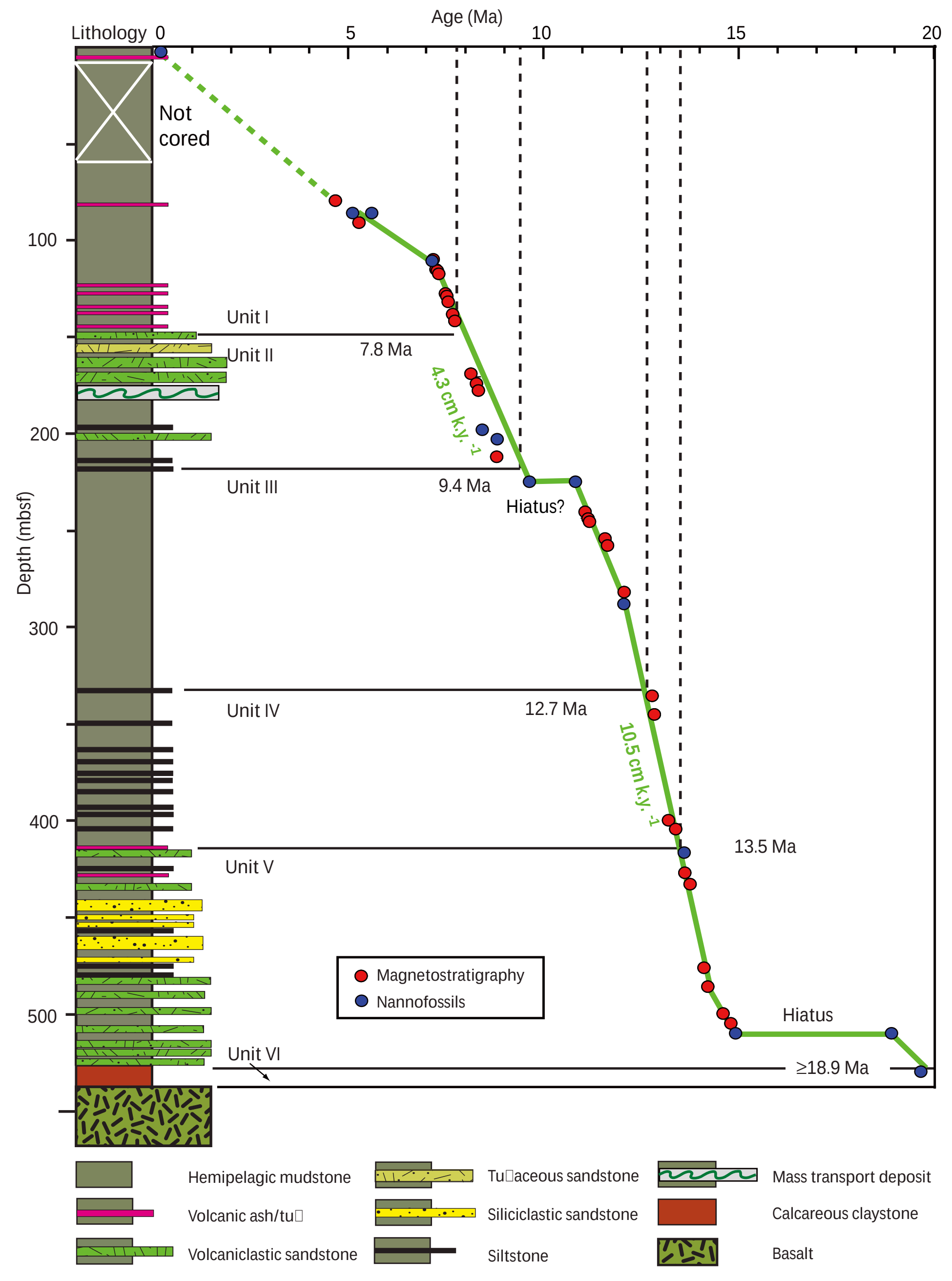

Figure 7. Integrated age-depth model for Hole C0012A using constraints from biostratigraphy and magnetostratigraphy.

Structures in the cores from Site C0012 consist of bedding planes, minor faults, and fractures. Most of the beds dip gently to the north, and seismic data show reflectors rolling over the crest of the knoll to the south-dipping flank just seaward of the drill site (Fig. 2). Steeper bedding dips (>25°) occur only in the upper part of Unit III, within the interval of inferred block sliding.

Physical properties data reveal depth trends similar to those documented at Site C0011, with gradual downhole increases in bulk density, electrical resistivity, thermal conductivity, and P-wave velocity, and a downhole decrease in porosity. Overall, these trends are consistent with normal consolidation, although multiple forms of drilling disturbance adversely affected data quality. Mudstone compressibility at Site C0012 is twice that interpreted for Site C0011, and there are several zones of anomalous porosity, including an interval from ~100 mbsf to 136 mbsf where changes in porosity are subdued. Porosity values are also abnormally high near the top of Unit V, these may help facilitate fluid migration at depth.

The results of interstitial water analyses from Site C0012 come as close as we can get to a true geochemical reference site for the Nankai Trough, and the problems encountered with contamination at Site C0011 are far less severe. The profile for dissolved sulfate shows quite a bit of structure, which is consistent with biogeochemical processes. The sulfate reduction zone is significantly deeper (~300 mbsf) than those detected at other sites along the Nankai margin. We suspect that subdued microbial activity in the upper sections of Hole C0012A is due to lower sedimentation rates above the basement high (Fig. 7), as compared to the flanks of the Kashinosaki Knoll where terrigenous organic matter is more voluminous (Fig. 4). Dissolved hydrocarbon gases were not detected in the upper 189 m of sediment, but increases in dissolved methane and ethane concentrations then begin to coincide with sulfate depletion at ~300 mbsf. The hydrocarbons at Site C0012 occur in significantly lower concentrations than at Site C0011, and gases heavier than ethane were not detected. One explanation for the presence of methane and ethane is up-dip migration of gas in solution from deeper thermogenic sources. Another possibility is *in situ* biogenic formation from terrigenous organic matter. Regardless of their origin, sulfate concentrations at Site C0012 are probably modulated by anaerobic methane oxidation (AMO), thereby leading to the production of hydrogen sulfide. In support of this idea, we observed a marked increase in hydrogen sulfide concentration concomitant with the peak in methane concentration, and pyrite is common in the sediments over a comparable depth range.

Unlike Site C0011, values of chlorinity at Site C0012 increase by about 12% relative to seawater. Values within Units I and II are uniform (~560 mM) and begin to increase below ~300 mbsf to the maximum value of 627 mM at 509 mbsf (Fig. 5). We suggest that this steady increase in chlorinity is a response to hydration reactions affecting dispersed volcanic ash and volcanic rock fragments (i.e., volcanic glass to smectite and zeolites) within Units IV and V. The trend of increasing chlorinity is unique with respect to other drilling sites on the Nankai trench floor and in the Shikoku Basin (including Site C0011), all of which show freshening at depth (Taira et al., 1992; Moore et al., 2001b) (Fig. 5). Regardless of the cause of freshening elsewhere, the absence of freshening at Site C0012 is important because it shows a lack of hydrogeologic connectivity between the northwest flank and the crest of the basement high. In addition, temperature-dependent alteration of volcanic ash and volcaniclastic sandstone probably controls changes in silica, potassium, and magnesium concentrations within the middle range of the sedimentary section. We attribute the documented depletion of dissolved sodium to formation of zeolites. Increases in dissolved calcium, which begin in Unit I, are probably overprinted at greater depths by deep-seated reactions in the basal pelagic claystone. The high concentrations of dissolved calcium help explain the precipitation of $CaCO_3$ as thin layers and nodules, even at very low alkalinity (<2 mM). In addition, all of the profiles of major cations and sulfate show reversals toward more seawater-like values within the lower half of lithologic Unit V. We tentatively attribute this shift to the presence of a seawater-like fluid migrating through the upper basaltic crust and diffusive exchange through the turbidites of lithologic Unit V. The hydrology responsible for this pattern, including potential recharge and discharge zones for fluids within upper igneous basement, remains unidentified.

## History of Sedimentation and Fluids Around Kashinosaki Knoll

Figure 8 shows the provisional correlation of units and unit boundaries at Sites C0011 and C0012. Recovery of the basal pelagic deposits in contact with pillow basalt at Site C0012 constitutes a major achievement. From this we know that the age of the basement is older than ~18.9 Ma, but radiometric age dating will be needed to establish the eruptive age. After a brief period of pelagic settling, a long interval of mixed volcaniclastic/siliciclastic sedimentation began. The turbidite section was interrupted near the crest of Kashinosaki Knoll by a hiatus of ~4 m.y., but this is probably a consequence of local mass wasting. Deposition of the sandy to silty turbidites in the lower Shikoku Basin seems to match up with broadly coeval siliciclastic turbidites at Site 1177 (Ashizuri transect of Nankai Trough). The subsequent transition into a long period of hemipelagic sedimentation is reminiscent of a similar lithologic transition at other sites in the Shikoku Basin, but the ages are different: ~7.0 Ma to ~2.5 Ma (Site 1177) versus ~12.7 Ma to ~9.1 Ma (Sites C0011 and C0012). The middle Shikoku Basin facies (Unit II) is unique to the Kumano transect area based on its age (late Miocene) and volcanic sand content. The closest volcanic terrain at that time was probably the Izu-Bonin arc, which we interpret to be the primary source for the volcaniclastic turbidites. Sedimentation decelerated again to a regime of hemipelagic settling and air-falls of volcanic ash (upper Shikoku Basin facies) beginning at ~7.8 Ma and continuing through the Quaternary.

When viewed as a pair of sites, it is clear that the condensed section at Site C0012 displays significant reductions in unit thickness and average sedimentation rate for all parts of the stratigraphic column, relative to the expanded section at Site C0011 (Fig. 8). The basement architecture clearly modulated sedimentation rates throughout the history of the Shikoku Basin, but relief on Kashinosaki Knoll was never high enough to completely prevent the transport and deposition of sandy detritus atop the crest. This comes as something of a surprise, although comparable deposits from thick turbidity currents and/or upslope flow of gravity flows have been documented elsewhere (Muck and Underwood, 1990). This discovery is important because the basement highs of the Shikoku Basin could act as asperities once they reach seismogenic depths along the plate interface (Cloos, 1992; Bilek, 2007). The thickness, texture, and mineral composition of sedimentary strata above such subducting seamounts probably contribute to variations in friction along the fault plane.

The interactions among sedimentation, basement topography, and diagenesis set up an intriguing possibility of multiple fluid regimes within the Shikoku Basin (Fig. 5). We need *in situ* temperature constraints and refined shore-based analyses to interpret the geochemistry with greater confidence, but one regime is modulated by compaction and mineral dehydration reactions. Fluid freshening and generation of heavier hydrocarbons (ethane, propane, butane) may be occurring at greater depths (i.e., below the trench wedge or frontal accretionary prism) in concert with up-dip migration toward the Shikoku Basin through high-permeability sand-rich facies. No such freshening, however, is observed in the condensed section at Site C0012 (Fig. 5). Unlike its flanks, the crest of Kashinosaki Knoll reveals a separate pore water regime driven by *in situ* hydration reactions and diffusional exchange with a higher-chlorinity, more-seawater-like fluid that is migrating through the underlying igneous basement. In essence, that site is a bona fide pre-subduction geochemical reference site for the Nankai subduction zone, with pore fluid chemistry unaffected by diagenesis and/or focused flow closer to the prism toe. The observed increase in sulfate below 490 mbsf is especially noteworthy; it cannot be supplied by the fluids with high concentrations of methane that exist on the deeper landward side of the seamount. Furthermore, we see an increase in hydrogen sulfide produced by AMO in the sediments above 490 mbsf, which argues for a sustained presence of sulfate below 490 mbsf. The sulfate must be replenished by active flow of methane-impoverished fluids within the highly permeable basalt below. This discovery is also very significant because it sets up the possibility of having hydrothermal circulation in the upper igneous crust (Spinelli and Wang, 2008; Fisher and Wheat, 2010) continue to modulate the hydrogeology and fluid chemistry of a subduction margin even after seamounts on the downgoing plate are subducted. This scenario of basement-hosted fluids is particularly intriguing at the seismogenic depths of the Nankai Trough, because the plate interface there is positioned at or near the top of igneous basement (Park et al., 2002).

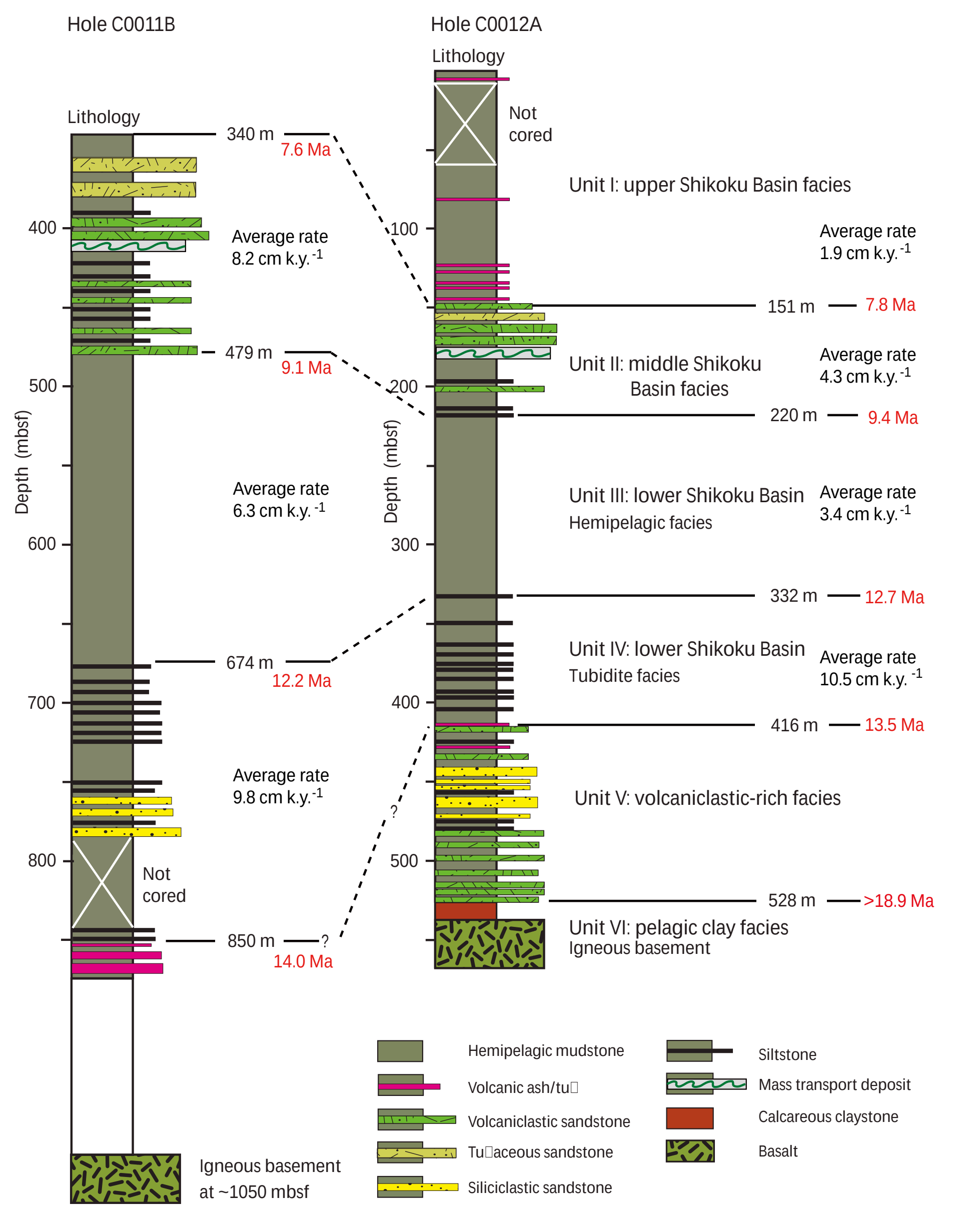


Figure 8. Stratigraphic correlation between Sites C0011 and C0012. For Site C0011, logging-while-drilling data only from 0 mbsf to 340 mbsf. Unit boundary ages taken from integrated age-depth models (biostratigraphy and magnetostratigraphy).

## Plans for Future Drilling

By drilling and coring two sites on the incoming Philippine Sea plate, we captured most of the fundamental compositional, geotechnical, and fluid properties of the Shikoku Basin that are likely to change down dip along the key stratigraphic intervals through which the Nankai plate boundary passes. In the future, IODP Expedition 333 will need to fill in some of the disconcerting gaps in coring and logging that remain from washed-down intervals and operational difficulties, and we must complete some much-needed measurements of borehole temperature to assess thermal history and the extent of in situ diagenesis. In the meantime, Expedition 322 will segue into a broad range of shore-based laboratory projects aimed at evaluating the many interwoven factors that collectively govern the initial, pre-subduction conditions. By expanding our collective knowledge of the subduction inputs, the NanTroSEIZE project will eventually be able to refine the observational and theoretical context for deep and ultra-deep riser drilling (Tobin and Kinoshita, 2006b), with the ultimate aim of understanding why transitions in fault behavior change from stable sliding to seismogenic slip (Moore and Saffer, 2001).

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# The New Jersey Margin Scientific Drilling Project (IODP Expedition 313): Untangling the Record of Global and Local Sea-Level Changes

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## Introduction

Much of the world is currently experiencing shoreline retreat due to global sea level rising at the rate of 3–4 mm yr$^{-1}$. This rate will likely increase and result in a net rise to roughly 1 m above present sea-level by the year 2100 (e.g., Rahmstorf, 2007; Solomon et al., 2007), with significant consequences for coastal populations, infrastructures, and ecosystems. Preparing for this future scenario calls for careful study of past changes in sea level and a solid understanding of processes that govern the shoreline response to these changes. One of the best ways to assemble this knowledge is to examine the geologic records of previous global sea-level changes. Integrated Ocean Drilling Program (IODP) Expedition 313 set out to do this by recovering a record of global and local sea-level change in sediments deposited along the coast of eastern North America during the Icehouse world of the past 35 m.y. What we learn from this record—the factors driving sea-level changes, and the impact of this change on nearshore environments—will help us understand what lies ahead in a warming world.

Eustatic history can be derived from three archives: corals, oxygen isotopes, and shallow-water marine sediments. Corals provide the most direct and detailed record (millennial-scale resolution or better), but it can be traced back no farther than latest Pleistocene (Fairbanks, 1989; Bard et al., 1996; Camoin et al., 2007). Oxygen isotopic ratios in carbonate-secreting organisms yield a glacio-eustatic proxy, but uncertainties arise further back in time because past water temperatures, which affect the oxygen isotopic ratio of seawater, are not known with sufficient accuracy. Furthermore, changes in the total volume of ocean water as inferred by oxygen isotopes are not the only eustatic drivers; the total volume of the world's ocean basins can change as well and impart eustatic change. For example, variations in the rate of seafloor spreading and in the amount of sediment deposited on the ocean floor affect basin volume and cause long-term (~10 m.y.) eustatic changes on the scale of tens of meters (Hays and Pitman, 1973; Kominz, 1984; Harrison, 1990) that are not accounted for by oxygen isotopic measurements.

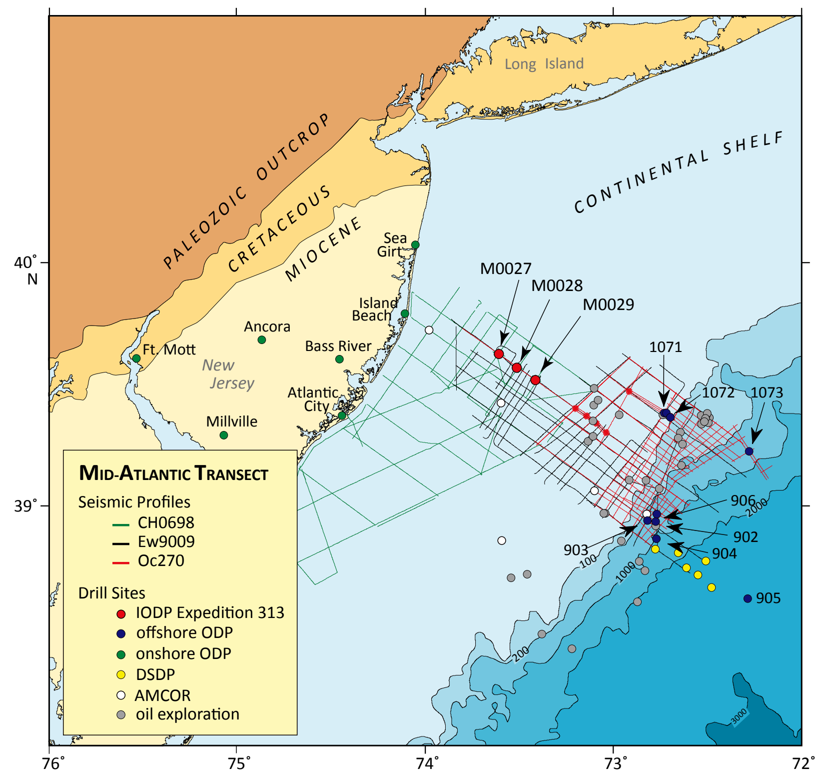


Figure 1. The New Jersey continental margin showing Sites M0027, M0028, and M0029 along with other completed boreholes both onshore and offshore. Tracks of reconnaissance seismic lines relevant to the goals of Expedition 313 are also shown.

The spatial and temporal arrangement of shallow-water marine sediments is a third archive of eustatic history. Their analysis is not a direct measure like corals, and it is rarely able to track changes at the Milankovitch scale that is possible with oxygen isotopes; however, the shallow marine sedimentary record can detect changes in water depth throughout the Phanerozoic and provide the sum of all processes that contribute to these changes and to the lateral migration of the shoreline. Therein lies the difficulty. Besides responding to eustatic change, the position of the shoreline and the accompanying change in facies respond to changes in sediment supplied to the coastal zone, compaction of deposited sediments, isostatic and/

or flexural loading of the crust, thermal subsidence of the lithosphere, and any other vertical tectonic motions of the basin. Furthermore, the magnitude of eustatic change is often considerably smaller than that of these other processes (Watts and Steckler, 1979), making the accurate measurement of this record a very challenging procedure.

Sloss (1963) cited eustasy as a possible cause of continent-wide unconformities dividing successions of shallow-water sediment across North America and Eurasia. His analysis suggested global sea level rose and fell in ~100-m.y. cycles throughout the Paleozoic. Other researchers reported that seismic profiles from sedimentary basins and continental margins revealed additional, globally correlated, unconformity-bound packages that indicated a higher-order cyclicity of eustatic change (~1.5 m.y.; Vail et al., 1977). By measuring variations in the elevation of what they termed coastal onlap seen in seismic profiles, they calculated that many eustatic oscillations were 100 m or more. Subsequent research showed, however, that the likelihood of shallow-water sediment accumulating along passive margins depends on the rate of eustatic change in relation to rates of change in sediment supply, basement subsidence, and compaction (Pitman and Golovchenko, 1983). This means that in the absence of detailed age control, compaction history, and paleo-water depth estimates, eustatic magnitudes cannot be derived directly from the architecture of stratal boundaries revealed by seismic profiles (Watts and Thorne, 1984).

Figure 2. L/B *Kayd* (Montco Offshore, Inc.) outfitted with a commercial drill rig using coring tools developed and operated by DOSECC, Inc., during Expedition 313 while under direction from ESO. It stands in 35 m of water 45 km off the New Jersey coast.

Despite an updated eustatic history based, as before, on patterns of coastal onlap, the underlying data was still proprietary (Haq et al., 1987), and researchers saw the need for passive margin records open to public scrutiny (Imbrie et al., 1987; Watkins and Mountain, 1990.) After many locations were evaluated, a transect across the New Jersey (NJ) coastal plain, shelf, and slope was chosen because of its relatively thick and continuous mid- to late-Tertiary section, lack of tectonic disturbance, wealth of background information, and mid-latitude setting that suggested a strong likelihood of yielding excellent geochronology and paleobathymetric control.

## IODP Expedition 313 Background

Ocean Drilling Program (ODP) Leg 150 (Mountain et al., 1994), benfited from earlier drilling (Deep Sea Drilling Project (DSDP) Legs 11 and 95; Hollister et al., 1972; Poag et al., 1987), and was the first step in the multi-leg New Jersey Transect designed to recover a record of eustatic history (Fig. 1). Leg 150 sampling was limited to the continental slope and rise, but it proved that sequence boundaries, defined by facies successions identified in cores and tied to seismic unconformities, coincided with increases in $\delta^{18}O$ that formed during times of glacio-eustatic lowering. Due to the distance from paleo-shorelines, these drill cores provided no information about magnitudes of eustatic change. ODP Leg 174A on the outer shelf attempted with limited success to sample more proximal Miocene sediments (Austin et al., 1998). Onshore drilling, sponsored by ODP, the International Continental Scientific Drilling Program (ICDP), the U.S. Geological Survey, and the New Jersey Geological Survey, cored equivalent sediments (Miller et al., 1998) and recovered vertical facies associations consistent with glacio-eustatic control. But due to their updip locations, each was stratigraphically incomplete, missing sea-level lowstands and lacking in seismic profiles that would otherwise place all in a broader context of stratal architecture. Nonetheless, calculations that removed the imprint of processes affecting the accumulation of Oligocene-Miocene sediments left 30–50 m sea-level changes that were assumed to be eustatic (Van Sickel et al., 2004). Offshore high-resolution profiles collected in 1995 and 1998 (Mountain et al., 2007; Monteverde et al., 2008) located clinoform topsets, foresets, and toesets of presumed Oligocene-Miocene age that, if sampled, would capture several complete Icehouse sea-level cycles. With the development of mission-specific operations in the IODP, three sites were selected in 2005 and placed on the schedule for drilling from a jack-up platform. It took until 2009 to secure a lift boat (L/B), drill rig, and crew under contract to the European Consortium for Ocean Research Drilling (ECORD) Science Operator (ESO) (Fig. 2).

## Scientific Objectives

Encouraged by the relatively well-known geologic setting of the NJ transect, and equipped with a platform immune to vertical and lateral motion and a drill rig well-suited for coring in sand-prone formations, Expedition 313 set out to overcome these challenges with the following objectives:

- Compare the age of Oligocene-Miocene Icehouse base-level changes with the age of sea-level lowerings predicted by the global $\delta^{18}O$ glacio-eustatic proxy
- Estimate amplitudes and rates and infer mechanisms of eustatic sea-level changes
- Evaluate models that predict litho-facies successions, depositional environments, and the arrangement of seismic reflections in response to eustatic change
- Provide a database to compare to sea-level studies on other margins

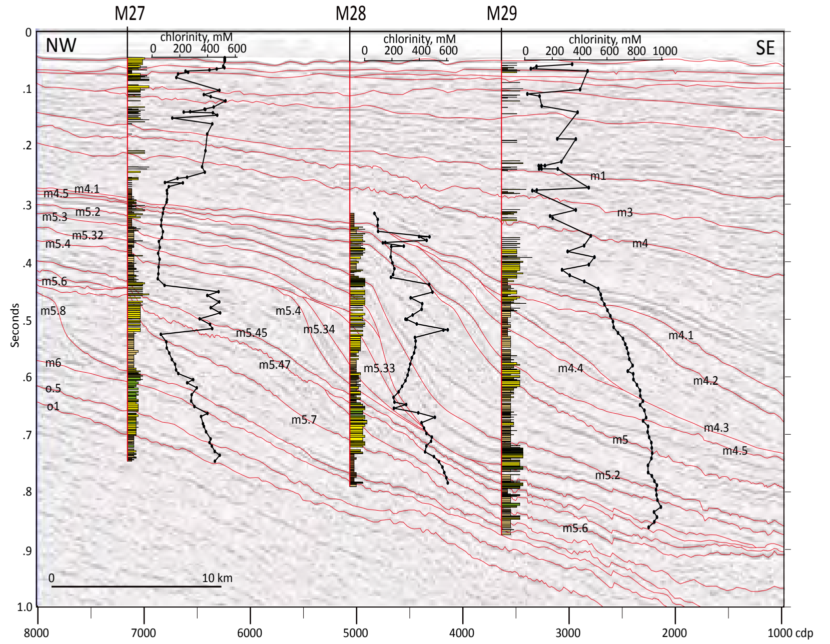

Figure 3. Seismic profile Oc270 line 529 that crosses the three Expedition 313 drill sites. Sediments between key Oligocene-Miocene sequence boundaries (labeled) and other mappable surfaces shown in red comprise many of the drilling targets. Recovered lithofacies (grain size in major units increases from left to right) and pore water chloride concentration are shown in travel time based on our preliminary acoustic travel time to depth-in-hole conversion.

## Operations

The L/B *Kayd* (owned and operated by Montco Offshore, Inc.) sailed north from the Gulf of Mexico and arrived in Atlantic City where offshore operations mobilized under contract to Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC). Operations began 45 km offshore on 30 April 2009 and continued until the return and demobilization at Atlantic City on 19 July 2009 (Table 1).

At each site conductor pipe was run 12–25 m into the seabed to stabilize the top of the hole and provide re-entry into the seabed for subsequent operations. Various biodegradable drilling fluids were used to condition the hole, cool the drill bit, and lift cuttings to perforations in the casing in the water column from which they settled out onto the seabed. Drilling and coring were conducted with 114.3-mm-diameter PHD drill pipe and top drive assembly commonly used in onshore mining operations. Hydraulic piston and extended-nose rotary coring similar to operations on the *JOIDES Resolution* were employed, but it was drilling with the extended, rotating coring "Alien" bit developed by DOSECC that proved most successful. Although the drill pipe became stuck numerous times, we had to abandon hope of freeing it only once (at 404 meters below seafloor [mbsf] in Hole 28A). In this case, narrower diameter (96-mm) HQ pipe and extended-nose rotary drilling continued to total depth through the center of the fixed PHD pipe. As anticipated in pre-expedition planning, to maximize operational time in the intervals of highest expedition priorities, we chose to spot core the top ~180–220 mbsf at each site (Fig. 3). Five types of wireline electric and imaging logs plus a Vertical Seismic Profile (VSP) were collected in segments at each site (Table 2, Fig. 4).

The onboard complement typically comprised the following personnel: 10 *Kayd* crew, 7–9 DOSECC drillers, 13–15 ESO staff, and 4–5 expedition science party members. Basic core curation, through-liner descriptions, measurements of ephemeral properties on un-split cores using the Multi-Sensor Core Logger (MSCL), and sampling at liner boundaries were conducted around the clock for the duration of offshore operations (Table 2).

Table 1. Expedition 313 Operations Summary (mbsl: meters below sea-level; mbsf: meters below seafloor)

| Hole | Latitude (N) | Longitude (W) | Water Depth (mbsl) | No. Cores | Total Hole Drilled (mbsf) | Total Core Attempted (m) | Total Core Recovered (m) | Total Core Recovered (%) | Total Hole Recovered (%) | Time on Site (days) |
|---|---|---|---|---|---|---|---|---|---|---|
| M0027A | 39°38.046067' | 73°37.301460' | 34 | 224 | 631.01 | 547.01 | 471.59 | 86.21 | 74.74 | 22 |
| M0028A | 39°33.942790' | 73°29.834810' | 35 | 171 | 668.66 | 476.97 | 385.5 | 80.82 | 57.65 | 28.7 |
| M0029A | 39°31.170500' | 73°24.792500' | 36 | 217 | 754.55 | 609.44 | 454.31 | 74.55 | 60.04 | 26.3 |
| Totals | | | | 612 | 2054.22 | 1633.42 | 1311.4 | 80.29 | 63.77 | 77 |

Table 2. Expedition 313 Measurements Summary

| | L/B *Kayd*, Offshore New Jersey | Onshore Science Party, Bremen | Moratorium Studies |
|---|---|---|---|
| **Lithostratigraphy** | Core catcher description<br>Smear slide identification<br>Core catcher photography | Split-core visual description archived according to IODP protocol<br>Smear slides, thin sections, CT scans<br>Observations incorporated into facies model<br>Full core & close-up photography | Lithofacies (petrography, sedimentary structures, etc.), depositional environment & sequence stratigraphic analysis<br>Ichnofacies & benthic macrofauna<br>Diagenetic alteration & cementation<br>Compaction & dewatering<br>CT scan analysis of sediment structure & texture<br>Semiquantitative petrography of coarse sediment<br>Quantitative clay mineralogy<br>Mapping Pleistocene valleys |
| **Biostratigraphy & Micropaleontology** | Benthic forams paleobathymetry<br>Planktonic forams biostratigraphy<br><br>Many samples (forams, palynomorphs, nannos) were taken from core catchers & some were analyzed before OSP | Additional sampling & sample preparation (primarily nannos, some forams & palynomorphs samples)<br>Biostratigraphic analysis of nannos, planktonic forams & dinocysts<br>Benthic forams paleobathymetry<br>Palynology paleoenvironments | Semiquantitative nannofossil biostratigraphy & paleoecology<br>Controls on planktonic foram abundance & diversity<br>Palynomorph taphonomy<br>Climate & sea-level controls on ecosystem evolution based on pollen (Eocene-Miocene)<br>Diatom & silicoflagellate biostratigraphy (mid-upper Miocene)<br>Amino acid racemization age dating (Pleistocene molluscs)<br>Radiolarian biostratigraphy |
| **Paleo-magnetism** | | Discrete measurements in fine-grained sediment<br>U-channel sampling | U-channel sample measurement & analysis<br>Detailed magnetic stratigraphy of selected sections (O/M transition, clinoform tops, etc.) |
| **Sr Isotopes** | 300 core catcher samples with shell material & benthic forams dated (using Sr) before OSP | Additional 900 samples taken | $^{87}Sr/^{86}Sr$ age dating of 900 samples of mollusks & benthic forams |
| **Downhole Logging** | Wireline logs, through pipe:<br>Spectral gamma ray (98%)<br>VSP (71%)<br>Wireline logs, open hole:<br>Spectral gamma ray (35%)<br>Induction resistivity (46%)<br>Magnetic susceptibility (47%)<br>Full waveform sonic (34%)<br>Acoustic imaging & caliper (34%) | | Refine VSP data to use up- & down-going energy for core-seismic correlation<br>Integration of acoustic images, depositional fabric & CT scans for core-log correlation<br>Synthetic seismograms & core-log-seismic correlation<br>Statistical analysis of log character & ties to lithofacies |
| **Core Logging** | Whole-core multi-sensor logging:<br>Density<br>P-wave velocity<br>Magnetic susceptibility<br>Electrical resistivity | Whole-core logging:<br>Natural gamma ray<br>Thermal conductivity<br>Split-core logging:<br>Color reflectance of split-core surface at discrete points<br>Continuous digital line-scanning of split core<br>CT-scanning (selected cores) | Lateral changes in physical properties<br>Core-log correlation<br>Comparison of core quality with MSCL measurements |
| **Petrophysics** | | Discrete sample index properties:<br>Compressional P-wave velocity<br>Bulk, dry & grain density<br>Water content<br>Porosity & void ratio | Changes of permeability, porosity & thermal conductivity with depth<br>Magnetic mineralogy & links to MSCL data<br>Cross plots of petrophysical data |
| **Geochemistry, organic & inorganic** | Pore water extraction with rhizome or hydraulic press:<br>Ephemeral pH by ion-specific electrode<br>Alkalinity by single-point titration to pH<br>Ammonium by conductivity<br>Chlorinity by automated electrochemical titration<br>Headspace samples for methane & stable carbon isotopes | IW analysis by ICP-AES & ICP-MS for 24 major & trace elements<br>Sediment TOC, TC, & TS by LECO (carbon-sulfur analyzer)<br>Sediment mineralogy by XRD (28 samples) | Relationship of sea-level change to phosphorus & organic carbon burial<br>Stable isotope (C, O, S) geochemistry of sediments<br>Nd & Os in sediment pore fluids<br>Quantitative assessment & carbon isotope stratigraphy of organic material (phytoclasts)<br>Iron-rich chlorite precursors in ichnofabrics<br>Full suite of elemental analyses & C isotopes of pore waters<br>Carbonates & other authigenic minerals<br>37Cl & origin of sediment porewater |
| **Seismic Stratigraphy** | Travel-time depth below sea floor relationship based on stacking velocities used as preliminary core-log-seismic correlation | Refined seismic-core correlations to improve agreement with lithostratigraphy & physical properties | Backstripping NJ transect compaction & subsidence history to estimate eustasy<br>Mapping seismic sequences on the NJ margin with ties to boreholes |
| **Microbiology** | Sampling & preparation of sediment samples | | Identification & quantification of phylogenetic groups of microorganisms (microscopic & molecular techniques) living in the subsurface |

Note: L/B, lift boat; CT, computed tomography; OSP, Onshore Science Party; O/M transition, Oligocene-Miocene transition; Sr, strontium; VSP, Vertical Seismic Profile; MSCL, Multi Sensor Core Logger; IW, interstitial water; ICP-AES & MS, Inductively Coupled Plasma Atomic Emission Spectroscopy & Mass Spectrometry; TOC, Total Organic Carbon; TC, Total Carbon; TS, Total Sulfur; XRD, X-Ray Diffraction; C, O, S, carbon, oxygen, sulfur; Nd, Os, Cl, neodymium, osmium, chloride. Numbers in parentheses equal percentage of total drilled section that was logged.

All cores and data were transferred to the Bremen Core Repository (BCR) at the end of the offshore phase. Additional measurements of natural gamma radiation, thermal conductivity, and computed tomography (CT) scans on selected cores were performed prior to splitting at the Onshore Science Party (OSP). The entire 28-member science party plus 37 others from the ESO and BCR plus student helpers met at the BCR from 6 November to 4 December 2009 to split, sample, and analyze the 612 cores and logs collected offshore (Table 2).

## Preliminary Results

Drilled-through and recovered sands. Interpreting the results of Exp. 313 began aboard the L/B *Kayd* by correlating the driller's reports of subsurface conditions with through-liner core descriptions, core-catcher samples, whole-round MCSL measurements, and inferences derived from seismic profiles (Fig. 3). The first strong reflector within a few tens of milliseconds below the seabed at each site indicated fine-grained, relatively firm sediment that provided a stable base for the conductor pipe designed to keep loose surficial sediment from caving into the hole.

The uppermost ~168–220 mbsf at all three sites contained few strong and continuous reflectors that would indicate regional stratal boundaries of interest and primary coring targets. Although we tried to core continuously in this shallowest interval at Site M27, unconsolidated and coarse-grained sediments led to slow difficult drilling and poor core recovery. This forced the eventual decision to drill without coring until we calculated we were approaching high-priority objectives. The equivalent stratigraphic units (based on seismic correlation) were drilled without coring at Site M28 and were only spot cored at Site M29; all information indicates these were upper Miocene to upper Pleistocene sands and gravels (we identified no Pliocene at any site) deposited in a range of shoreface, estuarine, fluvial, incised valley, and coastal plain environments. A possible paleosol was recovered in this spot-cored interval at Sites M27 and M29 at the depth calculated at both sites to correspond to seismic reflector m1.

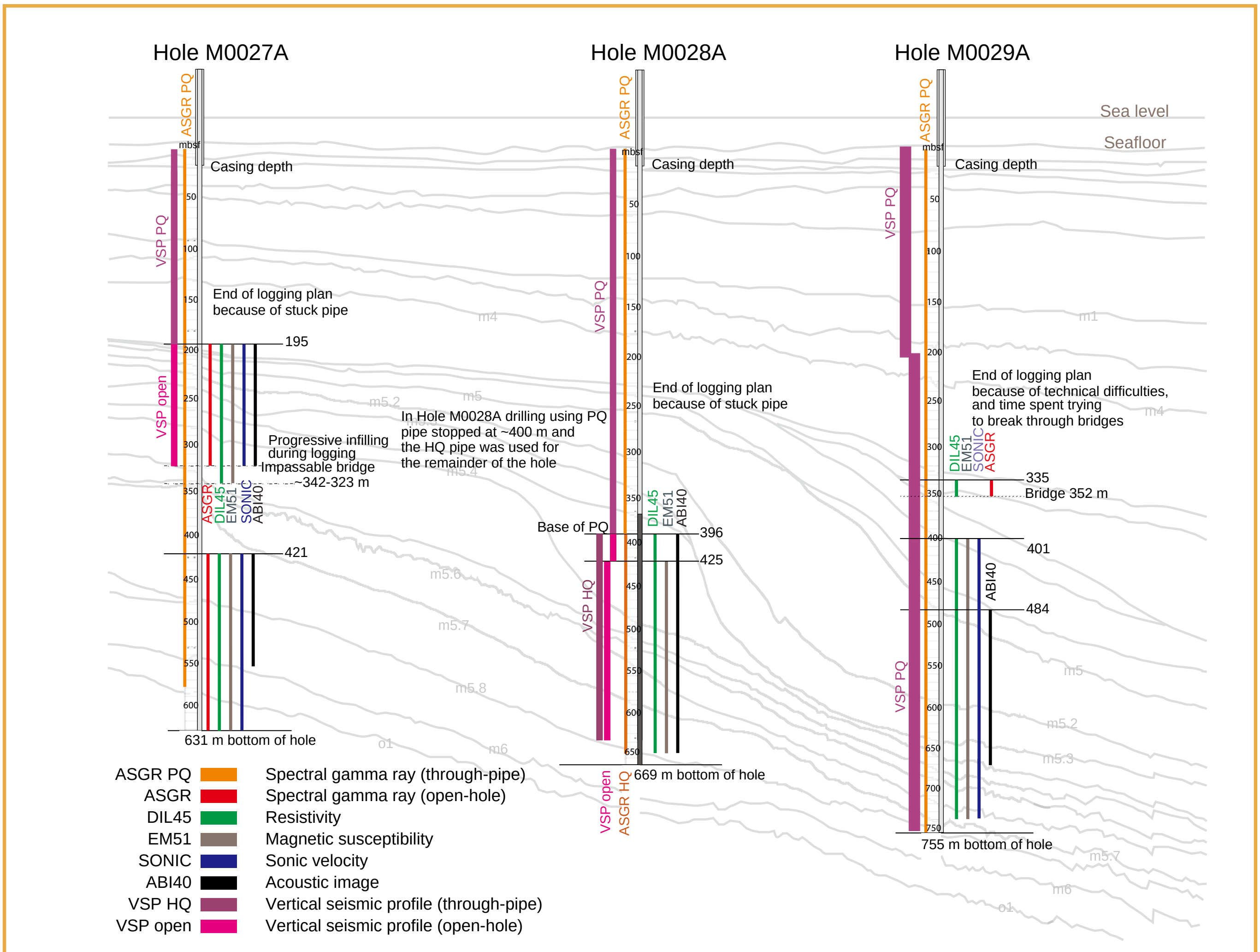


Figure 4. Graphic summary of downhole measurements from Expedition 313. Open-hole logging was planned and carried out in stages beginning with the lower section of each borehole. Vertical seismic profile (VSP) and through-pipe gamma logs are displayed to the left of the actual position of each borehole (gray column); open-hole logs are shown to the right. Vertical bars approximate positions of each measured interval. Gray reflectors in the background are the seismic sequence boundaries and other reflectors shown in Fig. 3.

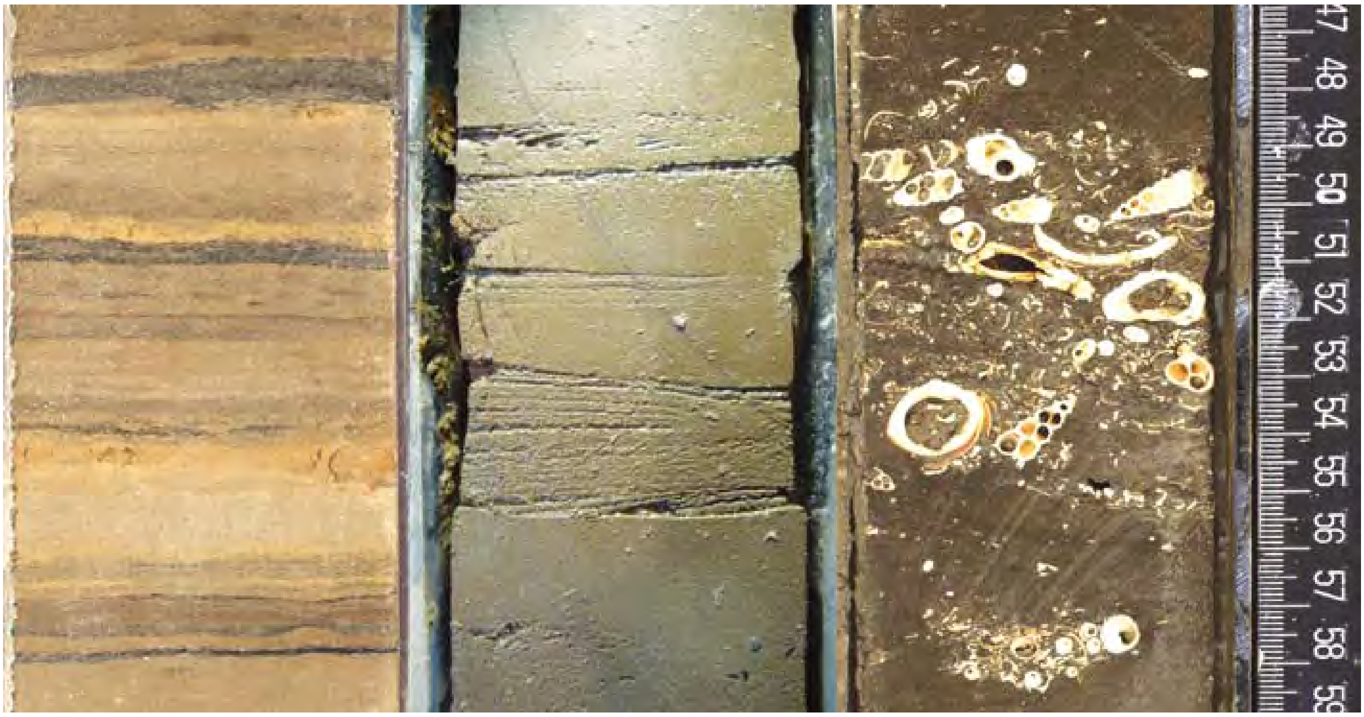

Figure 5. Close-up photographs of 3 split cores showing (from left to right): laminated silty clay from toeset beds seaward of a clinoform (Hole 28 core 166 sec 2); sharp-based sandy storm bed in sandy silt from topset beds (Hole 28 core 92 sec 1); and well-preserved gastropod and mollusk shells in silty offshore flooding surface (Hole 27 core 89 sec 1).

*Integrated seismic, log, and core information.* Prior seismic stratigraphy studies (Greenlee et al., 1992; Monteverde et al., 2008) identified probable sequence boundaries on the basis of seismic onlap/offlap patterns and ties to drill cores on the continental slope (Mountain et al., 1994). As a first approximation, stacking velocities from the processing of seismic data surrounding and passing through Exp. 313 sites were used to derive an acoustic travel time to depth-below-seafloor conversion. Check-shot VSP measurements at each site, plus physical properties measurements and synthetic seismograms, will firm up these preliminary seismic-core correlations in subsequent shore-based study.

As many as fifteen regionally mapped reflectors were intersected by one or more Exp. 313 drill sites (Fig. 3). Calculations using our preliminary time-depth equation provided expectations of depths at which surfaces and/or facies changes would be encountered, and typically these came within 5–10 m of a probable match in the cores, wireline logs, and/or MSCL measurements. In cases where seismic reflectors were especially closely spaced (vertical separation of <5 m), there remains uncertainty concerning which reflector ties to which geologic feature. Future work planned by the Exp. 313 science party will improve the reliability of correlations.

Petrophysical, MSCL, and downhole log data provided additional lithofacies characterization and greatly aided intersite correlations (Fig. 4). By providing continuous data for intervals with poor core recovery, logs enabled us to assign with reasonable confidence major seismic reflectors to depths where there was no core and hence no lithofacies feature to examine.

*Described and interpreted the lithofacies.* Sediments have been assigned to eight lithostratigraphic units that were deposited under two broadly defined conditions: (1) on a mixed wave- to river-dominated shelf where well-sorted silt and sand accumulated in offshore to shoreface environments and (2) during intervals of clinoform slope degradation that resulted in the interbedding of poorly sorted silts plus debris flow and turbidite sands with toe-of-slope silt and silty clays (Fig. 5). Deposits at all sites and all ages indicate a silt-rich sediment supply notably lacking in clay-sized components. Both *in situ* and reworked glauconite were common components of top-set and toe-set strata. The open shelf experienced frequent and sometimes cyclic periods of dysoxia. We found no evidence of subaerial exposure at the clinoform inflection point (depositional shelf break), but the periodic occurrences of shallow-water facies along clinoform slopes and of deepwater facies on the topset of the clinoforms suggest large-amplitude changes in relative sea level. Backstripping will provide estimates of the true eustatic component involved in the ~60-m changes in relative sea level observed on the shelf.

*Developed geochonology of the sedimentary record.* 1) Biostratigraphy: Roughly 300 samples were taken from core catchers on the *Kayd* and brought ashore for extraction of suitable mollusk shells and forams for Sr isotopic dating prior to the OSP in Bremen. Additional samples for palynomorphs, foraminifera, and calcareous nannofossils were also collected offshore and prepared prior to the OSP. Additional biostratigraphic control available at this preliminary stage comes largely from calcareous nannofossils sampled in split cores and analyzed during the OSP; as time allowed, a limited number of additional samples for planktonic foraminifera and palynomorphs were prepared and analyzed in Bremen. Additional biostratigraphic shore-based studies will be performed using diatoms and radiolaria. Amino acid racemization studies will be conducted on shells from the upper few tens of mbsf at Sites M27 and M29.

2) Magnetostratigraphy: Due to the paucity of fine-grained intervals and/or the lack of carrier minerals preserving a remnant signal, geomagnetic reversal chronology measured during the OSP was restricted to a few short intervals. More sensitive and time-consuming demagnetization techniques on discrete samples, as well as on U-channel samples, will be applied during post-OSP studies and may contribute further to Exp. 313 geochronology.

3) Sr isotopes: There is generally good agreement between the biohorizons of the different microfossil groups and the Sr isotope ages. One exception is within the thick Oligocene section at Site M27 where more shore-based analysis is warranted. The abundance and preservation of calcareous microfossils and dinocysts vary significantly, with barren intervals coinciding with coarse-grained sediments. Sr isotopic measurements provided ages that approached a precision of ±0.5 m.y. in some intervals and ±1 m.y. in others. A notable exception was the middle Miocene silty clay at Site M29 that showed substantial scatter. Microfossils are most abundant in this latter, most distal site, allowing for age refinements within the lower Miocene sections that proved barren of planktonic microfossils at the more proximal sites. Reworked Paleogene material occurs throughout the Miocene at all sites. A preliminary age-depth plot was developed in Bremen (Fig. 6) and will be refined when these additional shore-based studies are complete.

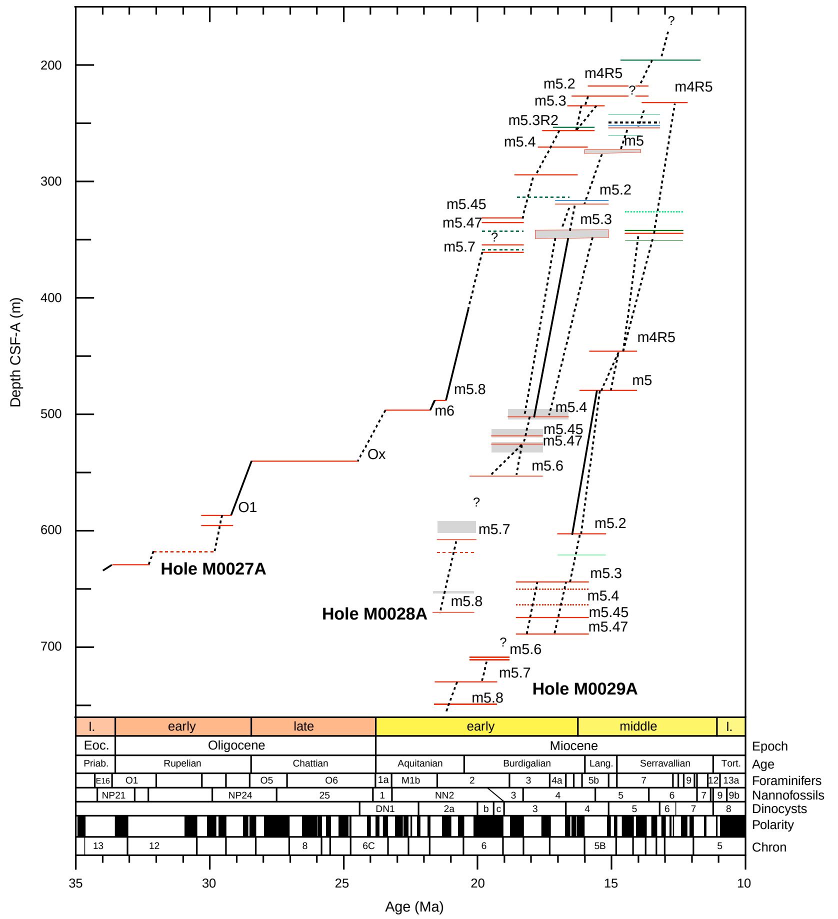


Figure 6. Expedition 313 chronology based on integrating biostratigraphy and Sr isotopic ages obtained at Sites M0027–M0029. Planktonic foraminifera M zone from Berggren et al. (1995), planktonic foraminifera E and O zones from Berggren and Pearson (2005), nannofossil zones from Martini (1971), and dinocyst zones from de Verteuil and Norris (1996). Geomagnetic polarity timescale from Cande and Kent (1995).

*Detected sea-level changes and paleoclimate.* Paleobathymetry and paleoenvironments determined from benthic foraminifers, dinocysts, and terrigenous palynomorphs track similar paleodepth variations at each site and in general agree well with paleobathymetric changes indicated by lithofacies. Values at each site range from inner neritic (0–50 m) to outer neritic (100–200 m). Paleodepth variations within individual unconformity-bound topset intervals suggest relative sea-level changes were as large as 60 m. While we detected mass failure of clinoform foresets, we found no evidence that sea level ever fell below the elevation of clinoform topsets. Water depth estimates based on benthic for-aminifers and palynological estimates of proximity to the shoreline show good to excellent agreement at all sites. Pollen studies identified a hemlock horizon across all three sites, indicating temperate forests and humid conditions on the Atlantic coastal plain during the early Miocene. Middle Miocene pollen assemblages record the expansion of grasses and sedges, indicating increasing aridity.

*Analyzed pore water chemistry.* Pore-water studies show that the upper several hundred meters of sediment at each site is dominated by freshwater interlayered with salt water of nearly seawater chlorinity. The abrupt boundaries between fresh and saline pore waters are especially remarkable (Fig. 3); whether they are maintained by dynamic flow/recharge or by strongly impermeable boundaries is not yet recognized. The pore water in these layers may have chemistries sufficiently distinct to enable correlation of individual layers from site to site; more shore-based analysis is required. Chloride concentrations increase with depth below seafloor, reaching seawater values in Site M27 and even higher concentrations in the other two sites. In Site M29, brine was encountered toward the bottom of the hole, reaching a chlorinity value twice that of seawater.

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Figure 5. by Gregory Mountain

# Establishing Sampling Procedures in Lake Cores for Subsurface Biosphere Studies: Assessing *In Situ* Microbial Activity

by Aurèle Vuillemin, Daniel Ariztegui, Crisogono Vasconcelos, and the PASADO Scientific Drilling Party

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## Introduction

Sub-recent sediments in modern lakes are ideal to study early diagenetic processes with a combination of physical, chemical, and biological approaches. Current developments in the rapidly evolving field of geomicrobiology have allowed determining the role of microbes in these processes (Nealson and Stahl, 1997; Frankel and Bazylinski, 2003). Their distribution and diversity in marine sediments have been studied for some years (Parkes et al., 1994; D'Hondt et al., 2004; Teske, 2005). Comparable studies in the lacustrine realm, however, are quite scarce and mainly focused on the water column (Humayoun et al., 2003) and/or very shallow sediments (Spring et al., 2000; Zhao et al., 2007). Thus, there is a need to determine the presence of living microbes in older lacustrine sediments, their growth, and metabolic paths, as well as their phylogenies that seem to differ from already known isolates.

During the PASADO (Potrok Aike Maar Lake Sediment Archive Drilling Project) ICDP (International Continental Scientific Drilling Program) drilling, more than 500 meters of sedimentary cores were retrieved from this crater lake (Zolitschka et al., 2009). A 100-m-long core was dedicated to a detailed geomicrobiological study and sampled in order to fill the gap of knowledge in the lacustrine subsurface biosphere.

Here we report a complete *in situ* sampling procedure that aims to recover aseptic samples as well as determining active *in situ* biological activity. Preliminary results demonstrate that these procedures provide a very useful semi-quantitative index which immediately reveals whether there are biologically active zones within the sediments.

## The PASADO Project

Laguna Potrok Aike is a 770-ka-old maar lake located at 51°58' S and 70°22' W in the Santa Cruz Province, Argentina, within the 3.8-Ma-old Pali Aike Volcanic Field (Fig. 1; Zolitschka et al., 2006). Although annual precipitation ranging between 200 mm and 300 mm gives a semi-arid character to the area, the lake is presently the only permanently water-filled lacustrine system in the southeastern Patagonian steppe. Today it has a maximum diameter of 3.5 km, a total surface of 7.74 km$^2$, and a maximum water depth of 100 m. The lake regime is polymictic, and the water-column is non-stratified with an anoxic sediment-water interphase.

A seismic study of this lacustrine basin showed a thick sedimentary sequence (Anselmetti et al., 2009; Gebhardt et al., in review) that was the target of the PASADO project. This international research initiative had a key objective: quantitative climatic and environmental reconstruction of this remote area through time. The multi-proxy study also provides unique material to initiate, for the first time in an ICDP project, a systematic study of the living lacustrine subsurface environment. From a total of 533 meters of sediment cores recovered at 100 m

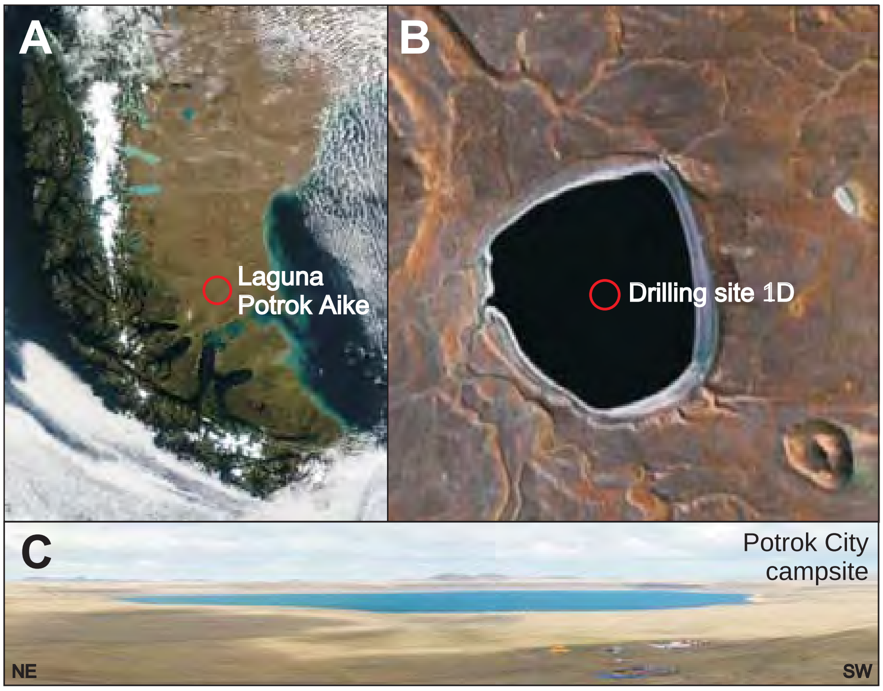


Figure 1. [A] Satellite image of Laguna Potrok Aike located in southernmost continental Patagonia, north of the Strait of Magellan, from http://www.zonu.com; [B] close-up of the lake showing the position of the drilling site discussed here, from http://earth.google.com; [C] panoramic view of the lake site with the field camp in the foreground.

water depth (Fig. 1), a one-meter-long gravity core PTA-1I and the 97-m-long hydraulic piston core PTA-1D were sampled following a newly established strategy to obtain aseptic samples for geomicrobiological studies.

## Sampling Procedure

A procedure was designed to minimize contamination risks in the field and laboratory. The size and configuration of the drilling platform prevented the setting up of a sampling laboratory with maximum conditions of asepsis. Thus, the retrieved cores were transported every 90 min from the platform to a laboratory in the campsite where they were sampled (Fig. 2). The liners of hydraulic cores were first disinfected with isopropanol and then sprayed with fungicide. Thereafter, cut in the liner using a portable circular saw every one or two meters and at higher resollution for the upper 15 m (Fig.3). Conversely, in the gravity core twenty windows were cut at 5-cm spacing in the empty liner and sealed with strong adhesive tape prior to coring. This latter technique facilitated opening windows and allowed sampling quickly at a higher resolution. Samples from these windows were immediately chemically fixed and/or frozen, optimizing the preservation of their initial conditions for further analyses.

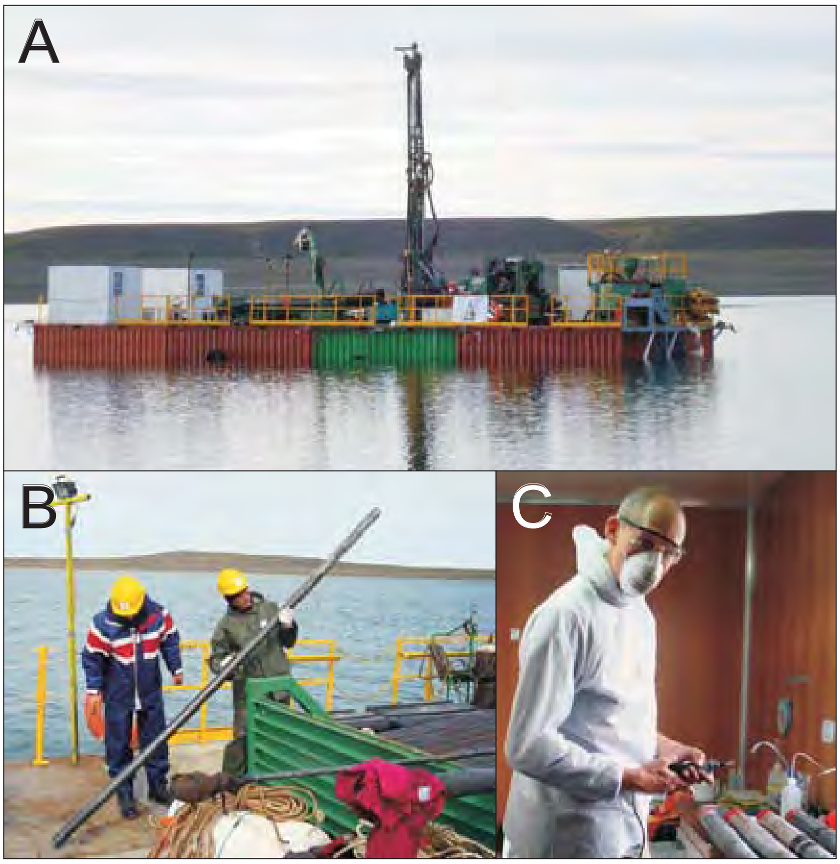


Figure 2. [A] Drilling platform GLAD 800. After retrieval [B], the cores were transported from the platform to the laboratory where they were sampled at once [C].

A rapid biological activity test, which is commercially available for industrial hygiene monitoring, was applied immediately after coring in order to test for microbial activity in the sediments. *In situ* adenosine-5'-triphosphate (ATP) measurements were taken as an indication of living organisms within the sediments. The presence of ATP is a marker molecule for metabolically active cells (Bird et al., 2001), since it is not known to form abiotically. ATP can be easily detected with high sensitivity and high specificity using an enzymatic assay (Lee et al., 2010).

ATP + luciferin + $O_2$ –> AMP + oxyluciferin + PPi + $CO_2$ + light

ATP is degraded to adenosine monophosphate (AMP) and pyrophosphate (PPi) while luciferin is oxidized. Light is emitted as a result of the reaction, and the light is detected by a photomultiplier. We used the Uni-Lite® NG Luminometer (Biotrace International Plc, Bridgend, U.K.), in combination with the "Clean-Trace" and "Aqua-Trace" swab kits (3M, U.S., Fig. 3E). The sensitivity of the test is on the order of $10^{-20}$ moles of ATP per mL of water, corresponding to a standard of 5 cells of *Escherichia coli* as expressed in RLU (relative luminescence units). This handheld device was previously tested at the Geomicrobiology Laboratory, ETH Zurich (Switzerland), where it was determined that this method could be applied on geological material such as rock surfaces and other environmental biofilms. It was also successfully used for fast and accurate measurements of life activity for freshly retrieved cores in lithified sediments of the IODP Expedition 310 in Tahiti (Camoin et al., 2007). The performance of this instrument in fresh sediments was uncertain, however, and to our knowledge this is the first time that it was successfully applied to lacustrine sediments. Additionally, the application of this test to water samples can aid in the evaluation of

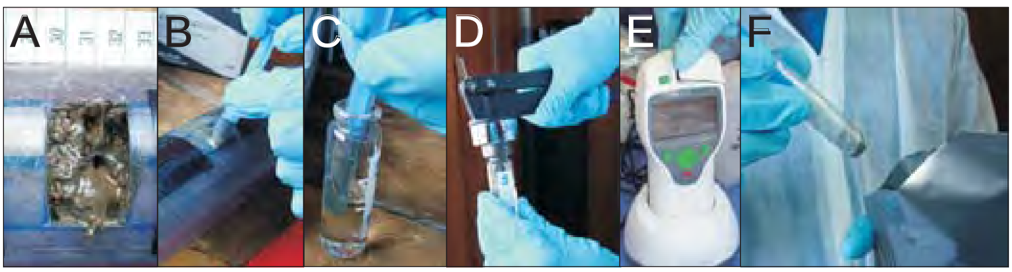


Figure 3. [A] Window cut for sampling; [B-D] sampling for methane headspace determinations; [E] preparation of the sample for *in situ* ATP measurements: sample is mixed with deionized water prior to centrifugation, then tested with the Uni-Lite® NG water tester (shown); and [F] storage of the remaining sediment for cell culture. Refer to text for details.

the degree of contamination of the drilling water which percolates along the inside of the core liner.

Figure 3A-3F summarizes the sequence and sampling procedures established in this project. Part of the sampling required precise volumes that were obtained using sterile syringes. Thus, samples of 3 mL and 5 mL of sediment were extracted from freshly opened windows using these syringes whose narrow tips were cut off in order to collect "mini-cores" (Fig. 3B). The first extracted sample was designated for methane analyses because of its immediate release into the environment due to volume expansion when exposed to ambient pressure. Hence, a portion (3 mL) of this first sample was chemically stabilized using 10 mL of 2.5% sodium hydroxide, and then sealed in vials for headspace analysis (Figs. 3C and 3D). The sediments were further sampled for different techniques using 5-mL syringes and portioned out as follows: the first 1-mL portion of sample was placed in an Eppendorf tube and kept frozen for further DNA extraction; a second 1-mL portion was chemically fixed in formaldehyde (final concentration, 2%) for DAPI (4',6-diamidino-2-phenylindole) cell count; a third 1-mL portion of the sediment was mixed with 1-mL of deionized water in an Eppendorf tube and centrifuged for five minutes. Commercially available water testers (Biotrace International) were carefully submerged in the supernatant, and ATP content was measured with the Uni-Lite® NG luminometer as an index of *in situ* microbial activity (Fig. 3E). The remaining sediment in the syringe was coated with plastic foil and hermetically sealed into aluminum foil bags (Fig. 3F). These bags were flushed with nitrogen (to prevent oxidation) prior to sealing with a heating device. These samples can be further used for microbial culture experiments back at the home laboratory. Once the sampling was accomplished, the windows were sealed with strong adhesive tape. This sampling procedure was carried out non-stop over a 48-hour period. A comparable sampling procedure for marine sediments can be found in Bird et al. (2001).

## Assessing *In Situ* Microbial Activity in Sediments

The presence of nutrients as energy sources is critical, promoting an active behavior of the inner microbial communities within sediments. When certain nutrient concentrations are below a threshold, microbial metabolism and population density are lowered progressively as these microbial communities enter in dormant state. Thus, microbial communities in deep sediments can be considered as mainly oligotrophic and dormant.

The 97-m-long sediment core retrieved from Laguna Potrok Aike provided us the opportunity to identify a transition from a weak but active to a dormant state of microbial communities as reflected by *in situ* ATP measurements (Fig. 4A). These results were further compared with those from DAPI counting on the fixed samples carried out several months later in the laboratory (Fig. 4B). The DAPI fluorochrome dyes DNA without distinction—active, dormant, and dead cells, either eukaryote or prokaryote—and it is considered as a semi-quantitative index of cell density within the sediment. ATP and DAPI datasets, however, show an increasing trend from the sediment surface to ~6-m depth within sediments mainly composed of black mud and subject to gas expansion. The DAPI and ATP trends throughout depth suggest an exponential decrease in microbial activity that is most probably linked to a progressive compaction and gradual nutrient depletion within the sediments. There is, however, detectable microbial activity down to 40–50 m and recoverable DNA down to 60 m sediment depth.

The sediments recovered from Laguna Potrok Aike are dominantly argillaceous but are occasionally interrupted by coarser sandy layers associated to slumps triggered by erosional and/or volcanic activities (Zolitschka et al., 2009). The latter are very important since allochthonous organic matter is harder to degrade, and microbial pres-ervation is highly dependent on grain size. Different sediment features further

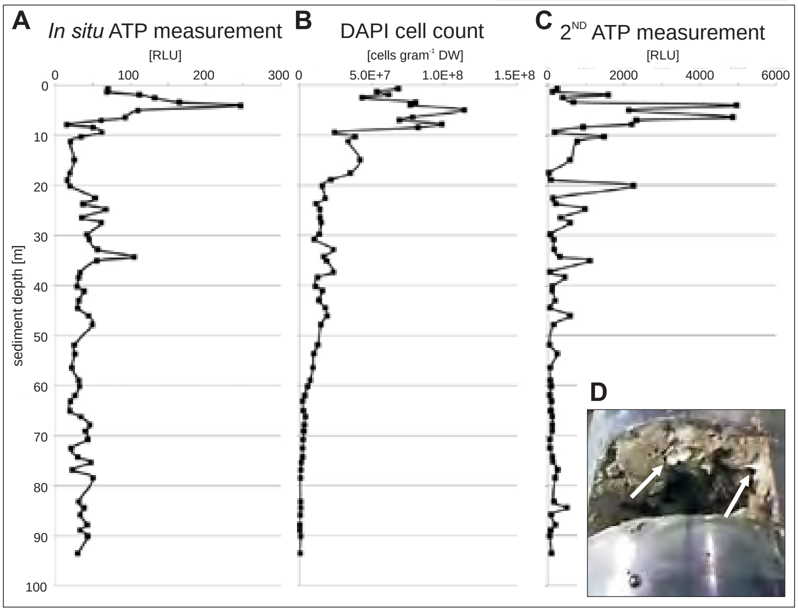


Figure 4. [A] The first ATP measurements were taken in an average of an hour and a half after each core recovery. They are considered as excellent indicators of *in situ* microbial activity. Noise was measured around 30 RLU (relative luminescence unit); [B] DAPI cell count provides a quantification of DNA present in the same samples; [C] second ATP measurements performed ten months later to test for eventual shifts in microbial activity. Although ATP indexes of active layers increased up to 20-fold, the originally nutrient-depleted layers remained inactive. Insert [D] shows a picture of mold (white arrows) which developed after exposure of the sediments to oxygen and pressure temperature (PT) ambient conditions. This partially caused the increased ATP values for the second run of measurements.

constrain microbial activity, as they provide colonization niches. Although microbial communities may adapt to trophic changes by shifting either their activity and/or dominant species, they are still highly representative of the lake catchment and their dominating climate. Ongoing multi-proxy analyses of these cores will allow char-acterizing the sedimentary sequence and provide the critical grounds to interpret the results of the observed microbial behavior.

## Validating *In Situ* ATP Measurements

Metabolic microbial activity can change drastically when samples are exposed to ambient temperature and pressure, light, and oxygen. In order to identify and possibly quantify the magnitude of these metabolic changes, a second set of ATP measurements was produced ten months after cores were retrieved (Fig. 4C). Both results indicate very similar distributions of microbial activity displaying the highest values at the same depths. In spite of the liner disinfection and the sealing of the sampling windows, mold had grown superficially on some windows, as shown in Figure 4D. The development of mesophilic aerobic microorganisms explains the comparatively higher ATP index of this second data set. These measurements warn about the omnipresent risks of contamination during sampling and further storage of the samples. They secondarily provide information about the nutrient resources of the sediments and their accessibility and use by microbes. Thus, this comparison between *in situ* and later ATP measurements highlights the relevance of the immediate measurement of microbiological living activity in the field. The comparison presented here between ATP values quickly obtained with a handset device further validates those *in situ* results produced by more established and tedious analyses such as DAPI cell counting of microbial cells.

## Future Improvements in Detecting the Living Biosphere in Lake Sediments

Lacustrine systems gather widely diverse water types such as brackish (Banning et al., 2005), acidic (Chan et al., 2002), hypersaline (Cytryn et al., 2000), or alkaline (Jones et al., 1998), among others. Each of them contains very different sediment and associated microbial assemblages. Understanding trophic states within the water columns and the sediments is essential to reconstructing past climates (Nelson et al., 2007) as well as to managing anthropogenic impact on modern lakes (Ye et al., 2009).

The assessment of microbial activity presented here provides information on various ongoing organic matter mineralization processes in the sediments and helps to understand the influence of microbes during early diagenesis. Our procedure can be easily applied as routine, adding valuable microbiological information that is complementary and relevant to several standard lacustrine proxies such as the stable isotope composition of authigenic carbonates and organic matter. Thus, the Uni-Lite® NG ATP tester is an excellent alternative to previously proposed complex ATP extractions (Stoeck et al., 2000; Bird et al., 2001; Nakamura and Takaya, 2003).

We are confident that the sampling protocol proposed here will allow scientists to sample cores in other ICDP projects with minimal contamination risks. It further points towards new research avenues and technical developments to better detect microbial activity and metabolic functions of the subsurface lacustrine biosphere.

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# Design, Manufacture, and Operation of a Core Barrel for the Iceland Deep Drilling Project (IDDP)

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## Abstract

The science program of the Iceland Deep Drilling Project (IDDP) requires as much core as possible in the transition zone to supercritical and inside the supercritical zone (>374°C), in the depth interval 2400–4500 m. The spot coring system selected has a 7 ¼" (184.15 mm) OD at 10 m length and collects a 4" (101.6 mm) diameter core using an 8 ½" (215.9 mm) OD core bit. It incorporates design characteristics, materials, clearances and bearings compatible with operation of the core barrel at temperatures as high as 600°C. Special attention was given to the volume of flushing which could be applied to the core barrel and through the bit while running in and out of the borehole and while coring. In November 2008 a successful spot coring test using the new core barrel was performed at 2800 m depth in the production well RN-17 B at Reykjanes, Iceland, where the formation temperature is 322°C. A 9.3-m hydrothermally altered hyaloclastite breccia was cored with 100% core recovery, in spite of it being highly fractured. A core tube data logger was also designed and placed inside the inner barrel to monitor the effectiveness of cooling. The temperature could be maintained at 100°C while coring, but it reached 170°C for a very short period while tripping in. The effective cooling is attributed to the high flush design and a top drive being employed, which allows circulation while tripping in or out, except for the very short time when a new drill pipe connection is being made.

## Introduction

In late 2003, a member of the IDDP consortium had offered one of its planned exploratory wells—RN-17, located on the Reykjanes peninsula—for deepening by the IDDP (Elders and Friðleifsson, 2005). It was drilled to 3.1 km depth, where it was planned to deepen it further some 2 km, partly by continuous wireline coring. The 3.1-km-deep well was flow tested in November 2005, and it collapsed during that test. In February 2006 the well had to be abandoned after several failed attempts at reconditioning. In 2008, the field operator decided to sidetrack this well southwards. During that operation the request by IDDP came to allow test-coring in this well with the new IDDP coring equipment.

Prior to the RN-17 borehole being occupied for the test spot coring, IDDP had determined that a deep borehole would be scientifically examined by the collection of core and logs. Cost constraints determined that continuous coring would not be possible and that a series of spot cores at strategic intervals would have to be collected. Further cost analyses indicated that it would be cost efficient to purchase a core barrel for the project and that the design could incorporate specific requirements for operation in deep, hot boreholes.

## Core Barrel Specifications and Manufacturing

The specification drawn up for international tender can be summarized as follows. A conventional core barrel is required for spot coring work in a deep scientific geothermal borehole. Temperatures in the borehole are expected to exceed 500°C, but with cooling and other measures currently employed in drilling shallower geothermal boreholes, it is hoped to keep coring temperatures below 200°C (Fig. 1). However, they could be as high as 250°C. The temperatures shown in Figure 1 are extrapolated from real data. They indicate the hole temperature over time when continually flushing while drilling or coring, and are the typical temperatures the core barrel could experience at the drilled depths shown. Data is verifiable to 2500 m from current drilling.

The outer core barrel is double-walled with (7" [177.8 mm] OD) with API thread and bit connections, and it has an overall length of 10 m. This overall length should be broken down to allow for efficient transportation and assembly and to incorporate top and bottom stabilizers, possibly a central stabilizer, and the opportunity to run a 5-m or 10-m assembly.

Rig configuration limits tubular handling operations and thus the maximum possible core barrel length to an effective 10-m core run. Stabilizers on the core barrel need to be compatible with coring operations with an 8½" core bit. Core barrel head or crossover sub-dimensions will be finalized when all rig tubular details are also known.

The inner core barrel produces a core of 4" (101.2 mm) diameter. The bearing assembly is water cooled and has no components susceptible to failure up to 250°C. During operation the barrel adjustments and tolerances must make allowance for core barrel heating, which can only be limited by the

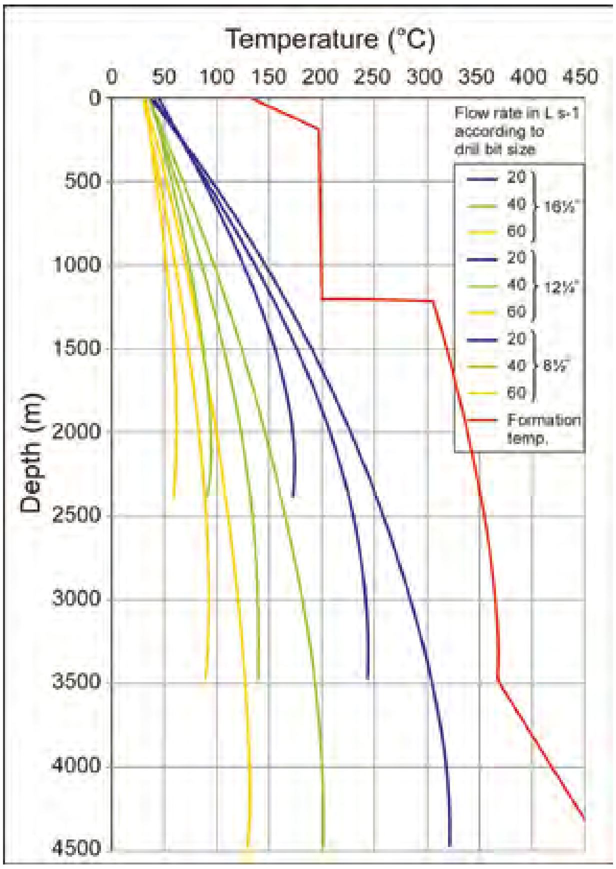


Figure 1. The anticipated temperature scenarios which any core barrel design has to meet.

water flushing. Figure 1 suggests that a minimum flushing capacity of 30–40 L $s^{-1}$ will have to be maintained for all of the tripping time and preferably for at least some of the coring time.

A conventional core spring type catcher and screw on shoe is essential. Other catcher options can also be considered as additions. Consideration may also be needed to keep the catcher shoe cool so it does not expand and interfere with core passage through it. Single or limited re-use inner core barrels will be considered if this is thought beneficial for annular clearances for flow requirements and if the wall thickness is too weak for robust use but sufficient for core collection and stability.

The core barrel should allow for a minimum of 30–40 L $s^{-1}$ flush while running string and should be able to accept 30 L $s^{-1}$ while coring (i.e., there must be sufficient annulus to allow bit cooling at this flush rate with no "lift-off" [hydraulicking]). Because of the danger of a blowout in the borehole, there will be check valves in the string and core barrel. These will preclude sending down steel balls to reduce flow to the core barrel prior to coring. In any event these would also preclude pumping at higher flushing rates should the string be held downhole or tripping delayed for longer than anticipated when the core barrel is attached.

Core bits to be designed for the core barrel have 8 ½" (215.9 mm) OD and (possibly) have peripheral and face discharge to accommodate the volumes of flush required without undue pressure or flushing loss at the bit cutting face. Only spot coring will be undertaken, and this is anticipated to be carried out only at drill bit changes or at other places where the geology may dictate, such as in a lost circulation zone where rock alteration properties would be investigated. Bit life but not robustness can be sacrificed for high penetration rates.

The formation is most likely to be basalt, dolerite, or gabbro as the borehole progresses. It may be fractured and have alteration zones in areas where there may be lost circulation. The rig top drive is well-instrumented and has good bit weight control. It is also capable of 140–200 rpm but using this speed may not be possible due to API string harmonics, and 70–100 rpm may be a more likely useable range. Weight on bit (WOB) can be well controlled, and an appropriate bottom hole assembly (BHA) to suit the bit can be made up, including uphole stabilizers (see below). Information gained from previous large-diameter coring suggests that surface set diamond bits performed well and polycrystalline diamond compact (PDC) bits less well due to breaking, although the penetration rate was good until this happened. Smaller diameter core bits using impregnated diamond bits perform very well and are robust. Provided the rig can accommodate the rotary requiremetnts of such bits, they should also be considered for this spot coring exercise.

Due to borehole depths (>3500 m) and slow drillstring trip times, it is not possible to clean the hole after drilling and before coring, unless there is significant metal junk in the hole, nor is it intended to drill a pilot hole to stabilize the coring bit at start. The core barrel and core bit should therefore be sturdy and aggressive enough to withstand some difficult conditions while establishing the coring regime. However, if the core bit can achieve this and make good penetration rate for 10 m of core, then this will suffice and the bit can be changed if necessary for the next spot core. In order for the project to be financially viable, a penetration rate (given suitable operating parameters) of 2.5 m $h^{-1}$ while coring should be targeted as a minimum in the formations indicated above.

According to the specifications, the core barrels were fabricated by Rok-Max Drilling Tools Ltd., and the core bits were made by GEOGEM Ltd., both UK companies with good track records in making specialist coring equipment and core bits. The core barrel is of all-steel construction. Bearings are heat-treated and plated to withstand an extremely harsh in-hole environment together with high operating temperatures. No rubber or plastic seals are used in its construction, and special high-temperature grease is used to lubricate the bearings and threaded components. It comprises an 11.6-m non-wireline conventional double tube corebarrel, with non-rotating inner tube assembly, and it is specifically

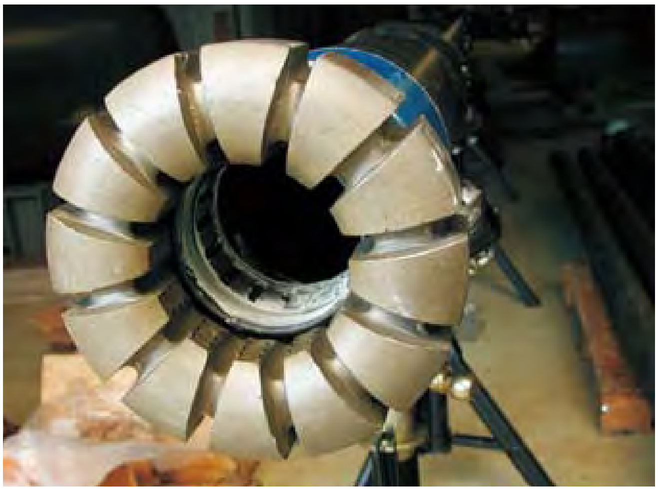

Figure 2. The core bit and core catcher assembly.

designed to take spot cores of 4" (101.6 mm) diameter x 10 m length and to give maximum flow through the core barrel of at least 40 L $s^{-1}$ flush for cooling. Special attention was given to the volume of flushing which could be applied to the core barrel and through the bit while running in and out and while coring. This in turn impacts on internal core barrel design of waterways and bearing configuration.

The core barrel bits for use with the system were designed with large waterways and a rounded profile crown to allow an element of hole cleaning when spudding in and maximum cooling when down hole. The composition is impregnated diamond with natural diamond and carbide gauging on both OD and ID. Matrix composition is designed for high-end temperatures and fast wear to allow clean fast cutting over the whole life of the bit. The design of the bit and matrix allows for a rotational speed of 70–160 rpm. The WOB should be 5.45–11.36 tonnes (12,000–25,000 lbs). Generally speaking, the higher rpm used, the lower the WOB, and *vice versa*, always within the given parameters. Flushing with rates as high as 40 L $s^{-1}$ do not hydraulically influence the bit performance; this was tested at the design stage by the manufacturer. A close-up of bit and core catcher is shown in Fig. 2.

The outer core barrel assembly comprises the following: bit, lower stabilizer section, lower outer barrel body, middle stabilizer section, upper outer barrel body, top stabilizer section, and core barrel head. Stabilizers and core bit are designed for 8½" (215.9 mm) hole size. There are no landing, latching, or stabilizing rings for the inner core barrel interconnected with the outer assembly. All materials, manufacture, and threads on the core barrel are to API specifications, but some internal core barrel threads are modified. The box thread and diameter on the core barrel head section of the outer core barrel are directly compatible with the drill collars being used. Two types were manufactured to accommodate 6¾" (171.5 mm) and 8" (203.2 mm) drill collar types.

The inner core barrel comprises a lower shoe which contains the core catcher or core spring, upper shoe, lower inner barrel stabilizer, lower core barrel section, middle stabilizer section, upper core barrel section, and core barrel bearing assembly. The bearing assembly housing screws into the outer core barrel head, and it is the only fixed point of contact with the outer core barrel. The bearings allow the inner barrel assembly to rotate freely within the outer tube, and adjustment on the bearing shaft ensures that the correct inner to outer spacings are set. The stabilizer sections keep the inner barrel central to the outer tube and the lower shoe. When the inner core barrel assembly length is adjusted via the bearing shaft, the face of the lower shoe sits inside the core bit throat with sufficient clearance for flush but not too much to hamper core ingress to the barrel. The core catcher design is "conventional" wedge spring catchers for competent formations. Heat treatment took into account metal fatigue and operating temperatures.

A digital temperature probe was designed and fitted into a pressure housing at the top of the inner barrel core chamber. Also within the pressure housing, a selection of temperature recording wax "spots" were inserted to allow a backup temperature reading to be recorded. Because this probe projects into the core chamber, it is not possible to take a full 10-m core run, as it could be crushed if full core recovery was achieved. Figure 3 shows fitting of the temperature probe.

Figure 3. Temperature logger.

## Spot Coring Operations

A spot core test was thought prudent as part of the operational planning for IDDP's planned drilling at Krafla, Iceland in order to try maximizing operational information and train the drilling crew in coring procedures. The main aims were as follows.

- Learn what may be the percentage core recovery, the core condition, information on core washing, bit performance and wear
- Approve the bit design based on grading of the used bit, so additional bits can be ordered
- Monitor the function of the core catcher and the bit cooling:
    - Inspect core barrel for adverse temperature effects
    - Read from temperature logger and temperature indicating strips/paint placed inside the core barrel
    - Determine how to optimize the bit cooling procedure with the top-drive while tripping in
    - Learn how much and how long to circulate at each stand
- Learn if any parts are missing or should be modified to speed up the handling of the core barrel
- Learn how to maximize the tripping speed
- Train the drillers and core hands in the proper coring procedures
- Collect information that can be put into a handbook for IDDP
- Collect information relative to 'risk assessment'
- Establish best parameters of rotation, WOB, and sensitivity of recording of parameters on the console to create a profile and add to procedures for spot coring on the full-scale IDDP-1 project in Krafla

The rig used for the spot coring is a Soilmech HH300 Drilling Rig with variable-speed top drive, automated pipe handling, and all safety features necessary for high pressure, high temperature geothermal well drilling. All rig tubulars are to API specification, and the rig crew is extremely competent in the handling and maintenance of all of the tools and machinery.

Data recording of drilling parameters was logged and made available for future analysis. A graphical output of drilling parameters is available to the driller during operation. Figures 4–6 have greatly assisted in allowing a full core barrel penetration to be achieved without any resistance to penetrate further.

Flush rate while coring was varied to observe any difference in core recovery results and recorded core barrel temperatures. The flush rates available while coring are very high compared to other core barrels, and high flush rates can affect both core recovery and penetration rates by washing away core and lifting the bit off cutting contact with the bottom, respectively. We used 40 L $s^{-1}$ while spudding in and for the first five minutes, then it was cut to 30 L $s^{-1}$ and after a few more minutes was reduced to 25 L $s^{-1}$ for the remainder of the coring run. No marked changes in bit weight or penetration rate were observed, so provided the formation is competent, there should be no problems in trying to core with full flush capability in boreholes which have a higher ambient temperature, such as that anticipated at Krafla. This suggests that the bit design meets requirements and allows for full flow through the waterways and then uphole without causing undue pressure build-up at the bit face or in the core barrel head ports.

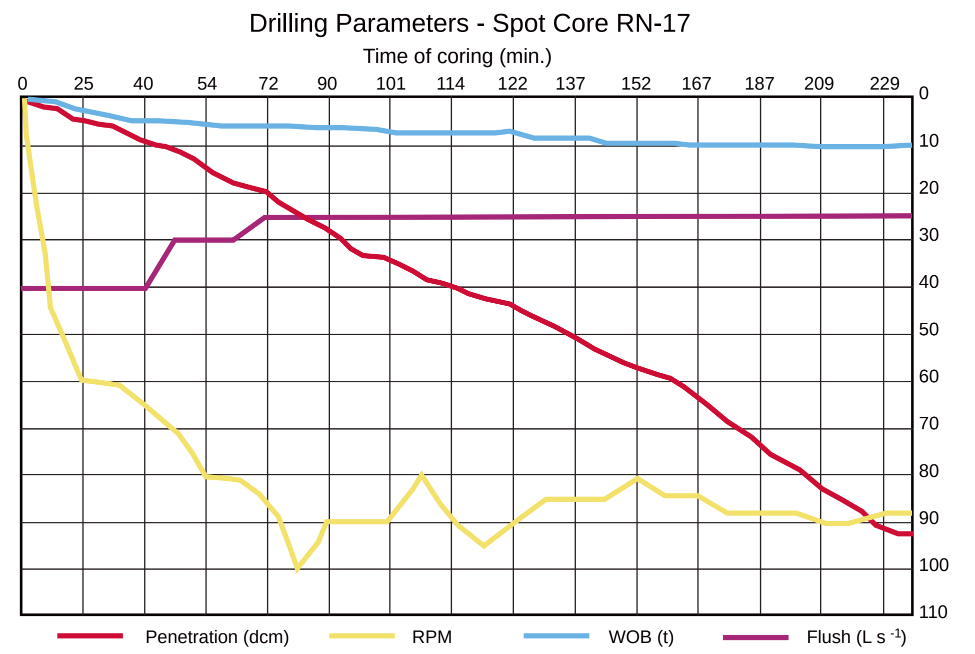


Figure 4. Smoothed drilling parameters recorded during the coring

It was not possible to reach and maintain high rotational speed (>100 rpm) on the drill string without excessive vibration and string movement. This could be due to a number of factors, but certainly the vertical to inclined borehole configuration would have something to do with this. However, rotation without excessive vibration or string movement was possible within the operating bit parameters. Generally if low-end rpm is used, then high-end bit weights have to be applied to maintain acceptable penetration and smooth operation.

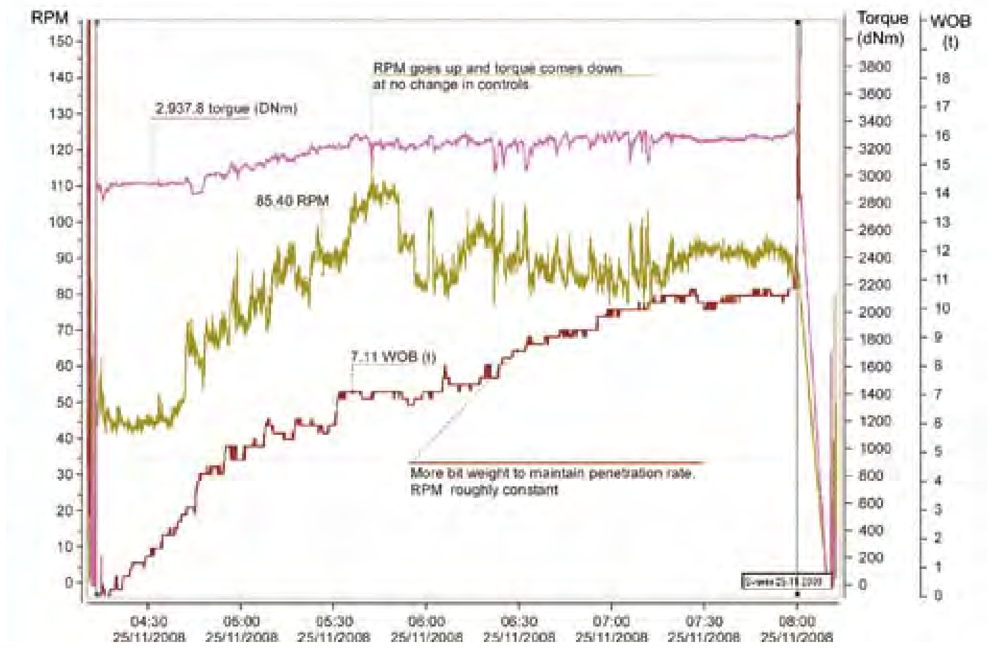


Figure 5. Weight on bit (WOB) (t), torque (dNm) and revolution (RPM) diagram during the test coring operation.

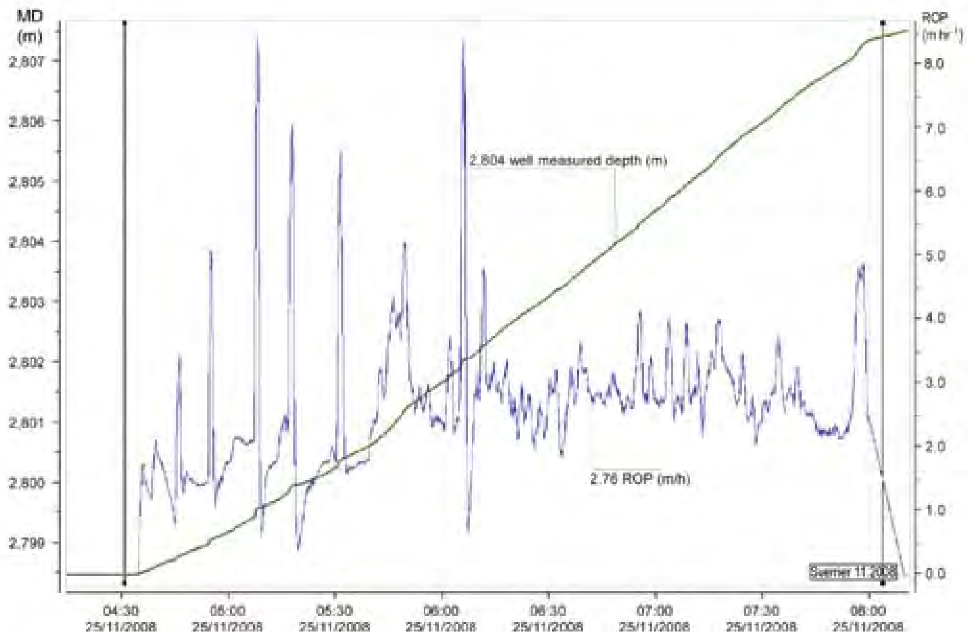


Figure 6. Time-coring rate (m $h^{-1}$) diagram – 27 November 2008, 4:34–8:00, at 2800 m depth. Core recovery was close to 100% of 4" core. Average coring rate 2.6 m $h^{-1}$. The green curve shows increasing depth.

## Spot Coring Results

Indications while coring suggested that core was being collected, but it was not until the pull-off force at the base of the coring run increased markedly then dropped back that it could be said that there was core caught inside the core barrel (which had to be broken off). Then it was not until the string was tripped out, the core barrel dismantled, and the core pumped out of the inner tubes that the full measure of the success of the core run was established.

Core recovery was excellent despite the fact that the core barrel was being run in an inclined borehole and the rock was fractured with many wedge-shaped planar fractures which could have easily caused core jamming. Figures 7 and 8 show the nature of the core collected. The cored section consisted of a hyaloclastite breccia, thoroughly altered to greenschist facies mineralogy. Apparently, this breccia was deposited in shallow marine environment, despite the fact it is now at 2.500 m depth below the surface. The age of this breccia is one of the key questions to be unraveled to allow estimation of the subsidence rate in the middle of the Reykjanes rift zone. The drill core is now being studied, and first results have been published by Friðleifsson and Richter (2010).

In the 35°-inclined RN-17 B test hole, the inner core barrel stabilizers could not operate properly as centralizers, since wear was always on the side "lying down". Although this did not materially affect the coring, it induced more refurbishment of stabilizers than would otherwise occur, and it may be that for inclined coring (not routinely planned) a set of stabilizer rings may have to be incorporated into the outer, rather than the inner, core barrel sections.

## Acknowledgements

The work was carried out to an agreed plan, schedule, and extremely tight timescale. The successful outcome is in

Figure 7. Core bit with core securely held in catcher.

Figure 8. Cores boxed for examination.

large measure due to the thought put into the core barrel and bit designs by ROK-MAX and GEOGEM companies and to the efforts of H. Guðmundsson regarding site management of equipment, logistics, and suitable location to set up and service the core barrels. The IDDP committees of Sciences Application Group of Advisors (SAGA) and Deep Vision approved the case for core barrel procurement, which was overseen by Bjarni Palsson of Landsvirkjun. At site the drilling manager, Steinar Már Þórisson, worked with us and both shift crews of the Jardboranir Ltd. drill rig Tyr to allow an excellent test with a good outcome.

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# Integration of Deep Biosphere Research into the International Continental Scientific Drilling Program

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## Introduction and Workshop Goals

An international workshop on the Integration of Deep Biosphere Research into the International Continental Scientific Drilling Program (ICDP) was held on 27–29 September 2009 in Potsdam. It was organized by the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences and the University of Potsdam (Germany). Financial support was provided by ICDP. This workshop brought together the expertise of thirty-three microbiologists, biogeochemists, and geologists from seven countries (Finland, Germany, Japan, New Zealand, Sweden, U.K., U.S.A.).

Over the last two decades, microbiological and biogeochemical investigations have demonstrated the occurrence of microbial life widely disseminated within the deep subsurface of the Earth (Fredrickson and Onstott, 1996; Parkes et al., 2000; Pedersen, 2000; Sherwood Lollar et al., 2006).

Considering the large subsurface pore space available as a life habitat, it has been estimated that the biomass of the so-called deep biosphere might be equal to or even larger than that of the surface biosphere (Whitman et al., 1998). Thus, the deep biosphere must play a fundamental role in global biogeochemical cycles over short and long time scales. Its huge size, as well as the largely unexplored biogeochemical processes driving the deep biosphere, makes the investigation of the extent and dynamics of subsurface microbial ecosystems an intriguing and relatively new topic in today's geoscience research. Our knowledge of the deep biosphere is still fragmentary especially in terrestrial environments. While geobiological research is already an integral part in many Integrated Ocean Drilling Program (IODP) sampling missions (Lipp et al., 2008; Roussel et al., 2008; Zink et al., 2003), only a few recent projects within the ICDP have had a geobiological component (Colwell et al., 2005; Gohn et al., 2008; Mangelsdorf et al., 2005). In the recently published book *Continental Scientific Drilling – A Decade of Progress and Challenges for the Future*, Horsfield et al. (2007) argued that exploration of the "GeoBiosphere" should be an integrated component of the activities of ICDP to correct this imbalance.

Thus, the aim of the workshop was to integrate deep biosphere research into ICDP by 1) defining scientific questions and targets for future drilling projects in terrestrial environments and 2) addressing the technical, administrative and logistical prerequisites for these investigations. According to these goals the workshop was segmented into two parts.

Figure 1. The Mallik Gas Hydrate Research project drill site at the northern edge of the Mackenzie River Delta, Northern Territories Canada. The Mallik project was one of the first ICDP projects containing a deep biosphere component.

## Key Scientific Questions and Identification of New Targets

*Topics for deep biosphere research in terrestrial systems.* With the discovery of deep microbial ecosystems in sedimentary basins–as well as microbial life in granites, deep gold mines, and oil reservoirs—the view of the scientific community was opened to a hidden and largely unexplored inhabited realm on our planet (Fredrickson and Onstott, 1996; Parkes et al., 2000; Pedersen, 2000; Sherwood Lollar et al., 2006). From a surface point of view the deep subsurface is an extreme environment. With increasing burial depth, microbial communities have to cope with increasing temperature and pressure, nutrient limitation, limited porosity and permeability as well as a decrease in the available carbon and energy sources, essentially affecting the composition, extent, life habitats, and the living conditions (Horsfield et al., 2007). The rates of microbial cellular activity in the deep biosphere are estimated to be orders of magnitude lower than those in surface environments. Contrary to surface microbes, which generally have doubling times of minutes to months, the average frequency of cell division of deep subsurface microorganisms is within the range of a century (Fredrickson and Onstott, 1996) and defies our current understanding of the limits of life.

In marine and terrestrial sedimentary basins, buried organic matter is the obvious carbon and energy source for deep microbial life. In the upper part of the sediment column it is thought that intense degradation of organic matter initially increases the recalcitrant proportion of the organic material. However, in deeper successions the bioavailability of organic matter might increase again due to the rising temperature with increasing burial depth, affecting the bond stability of potential substrates in the organic matrix (Parkes et al., 2007; Wellsbury et al., 1997; Glombitza et al., 2009). The organic matter in these ecosystems was initially produced by photosynthesis. Therefore, despite the long delay between production and consumption, these systems are ultimately depending on surface processes.

In environments with little buried organic matter—for instance, in igneous rocks—lithoautotrophic microbial communities are able to synthesize small organic compounds from inorganic sources like hydrogen gas and carbon dioxide, and these simple organic compounds can then be utilized by other heterotrophic microorganisms. Such microbial communities, also called Subsurface Lithoautotrophic Microbial Ecosystems (SLiMEs), form entire ecosystems in the deep subsurface, which are completely independent from photosynthetically produced substrates (Fredrickson and Onstott, 1996; Lin et al., 2005; Lin et al., 2006; Sherwood Lollar et al., 2006; Stevens and McKinley, 1995).

The widely disseminated deep biosphere poses fundamental questions such as the following. What kind of microorganisms populate the deep subsurface? What is their extension and where are their limits? How is their life habitat shaped? What metabolic processes do they perform? What carbon and energy sources do they use? What survival strategies do these microorganisms apply? Does microbial life in the subsurface represent early life on Earth? What is their impact on the global carbon cycle and linked to that on the global climate?

Deep microbes not only create (biogenic gas) but also have the potential to destroy fossil energy resources (biodegradation of oils). Also, research on potential life in the subsurface of other planets (e.g., Mars), studies about the safety of deep nuclear waste disposal sites, bioremediation of polluted sites, deep aquifer exploration, and the search for new biomedicals are drivers of deep biosphere research (Rothschild and Mancinelli, 2001).

Thus, the workshop participants defined general key topics for terrestrial deep biosphere drilling.

- Extent and diversity of deep microbial life and the limits of life
- Subsurface activity and metabolism as well as carbon and energy sources for deep microbial life
- Evolution, survival, and adaptation of deep microbial life
- Resources and applications: natural resources provided or degraded by deep microbial communities and the implication on biotechnology applications
- Interaction of the deep biosphere with the geosphere and implication of deep microbial activity on Earth's climate
- Deep biosphere as a model for early life on Earth and life on other planets

The workshop also addressed more specific topics including a potential target for already scheduled ICDP drilling campaigns of forming a base for a future dedicated ICDP deep biosphere project, and sampling and curation standards to support interoperability between different drilling operations.

*Diversity and extent of the deep subsurface biosphere.* One exciting question is whether deep terrestrial and lacustrine subsurface communities differ from the subseafloor biosphere (and if yes, how)? There are many structural corresponding subterrestrial and subseafloor environments (e.g., subsurface ecosystems in pressure enhanced hyperthermophilic systems and subseafloor hydrothermal vent systems) that allow a comparison of the indigenous subsurface and subseafloor microbial communities.

In addition to the spatial distribution and diversity of deep microbial life, the question on the temporal diversity in a given subsurface location due to changes in the environmental conditions was addressed. To monitor such changes, the installation of monitoring devices (e.g., osmo samplers), measuring the chemistry and flow rates of fluids, and the use of cartridges with different substrate media were suggested as part of the formation of a natural laboratory under *in situ* conditions.

While investigating the deep biosphere, participants focused on microbial communities. Other components such as phages were mainly overlooked. In the last few years the investigation of phages has become a new topic in deep biosphere research (Engelen et al., 2009). Viral infection of deep microbial communities was discussed as a controlling factor for the deep biosphere through exchange of DNA, killing microorganisms, and also providing essential substrates for non-infected microorganisms due to the viral-induced release of cell components from infected cells (the so-called viral shunt). Thus, this intriguing new scientific field should also form an integrated part of future deep biosphere research in terrestrial systems.

*Limits of subsurface life*. What determines the biogeography of microorganisms in the deep subsurface? Conceivable factors are the grain size, pore space, and permeability of the sediments and rocks. Furthermore, the content, distribution, and kind of organic matter—and, therefore, the availability of carbon and energy sources—as well as deep fluids and ambient temperature play a significant role with all having strong impact on the habitability in the deep realm. Knowing these factors, can we predict the distribution, extent, and composition of the deep microbial communities? Are deep biosphere communities exploiting all low temperature (<150°C) parts of the rock cycle, and how do the physical and geochemical characteristics of the habitat determine the abundance and distribution of the microbial communities?

In this context it is of interest whether paleopasteurization (Wilhelms et al., 2001) exists in, for instance, organic-rich sediments initially subsided to greater depth with corresponding high ambient temperatures and subsequent uplift into temperature regimes that are usually compatible with deep microbial life. Another aspect is how the biogeography of microbial communities of isolated (closed) terrestrial systems (e.g., no contact to meteoric fluid flows) differs from open systems in time and space, especially with respect to speciation and survival strategies (adaptation/repair mechanisms) in the deep biosphere. Are there ecological niches, and is there competition between the deep microorganisms affecting the community structure and evolutionary processes?

*Processes and interactions*. In sediments the deposited and subsided organic matter forms the carbon and energy sources for the indigenous microbial life. Initially, the recalcitrant proportion of the organic matter increases with ongoing subsidence and maturation. On the other hand, early geothermally driven degradation processes already start at comparable low temperatures (>50°C) gradually providing again potential substrates for the deep biosphere (Horsfield et al., 2006). Is there an overlap between biogenic and thermogenic processes being a feedstock for deep terrestrial microbial ecosystems, and what is the role and importance of geological processes to sustain biological systems in the deep biosphere?

As we examine the potential feedstock sources for deep microbial life, it is also of interest to investigate the impact of $CO_2$, $N_2$, and radioloytic $H_2$ production and/or $O_2$ generation on the metabolic processes and the composition of deep microbial ecosystems, such as in lithoautotrophic communities in a range of different subsurface systems (e.g., U-rich systems, seismically active zones, and high temperature (energy) regimes). What are the rates of formation of these "geogases", and how do the rates change with different settings, depth, and formation ages?

Oil, gas, and coal reservoirs form potential carbon and energy sources for deep microbial life. Thus, what is the relative importance of natural but also abiotic hydrocarbons for

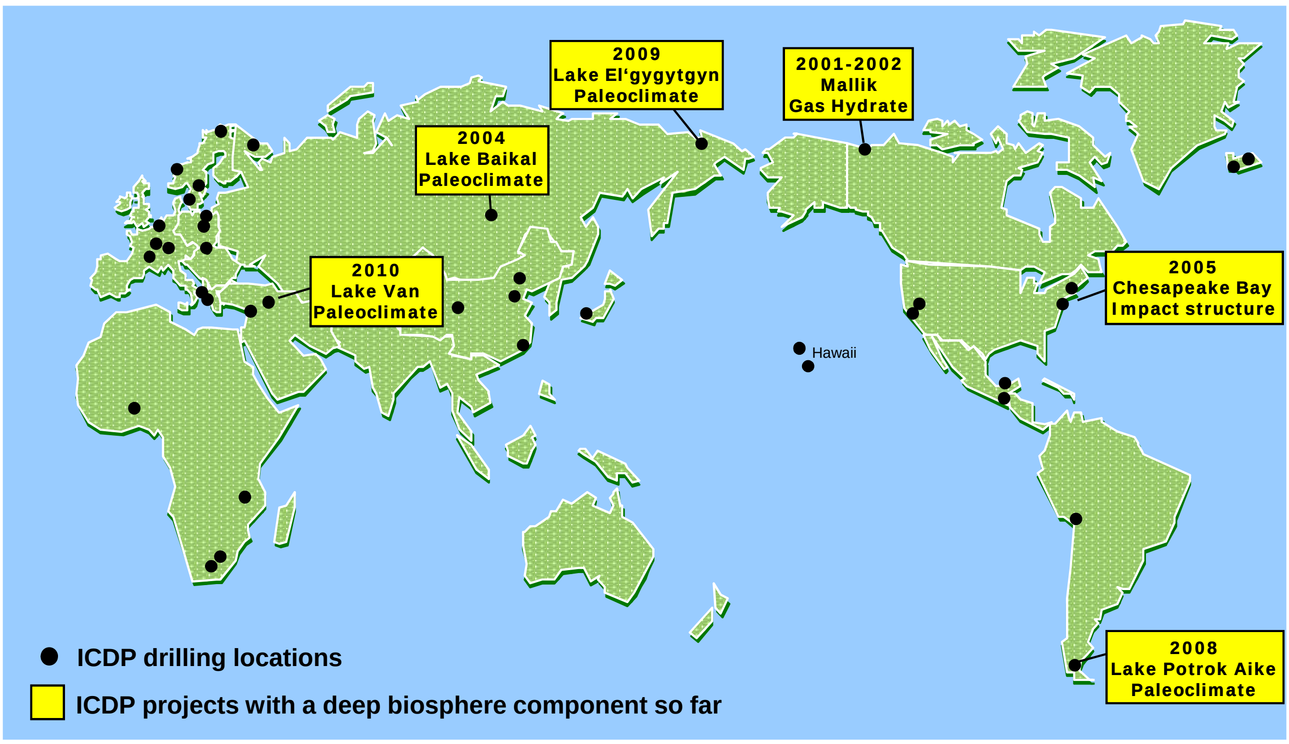


Figure 2. Map showing already completed ICDP projects with deep biosphere components (modified after Horsfield et al., 2007).

supporting deep microbial communities? What role do deep microorganisms play in the formation and destruction of natural resources (oil, gas, coal), and how do their metabolisms influence the geochemistry and mineralogy of the subsurface (i.e., the deposition of ores)?

Also of interest is how natural and human perturbation affect subsurface ecosystems in time and space. For instance, how do deep microbial communities respond to earthquakes, mobilizing fluids (geogases), the disposal of waste, or the sequestration of $CO_2$ (e.g., Ketzin, Germany or Columbia River basalts, U.S.A.)?

Microorganism populations interact with each other, and this raises further questions. What are the characteristics of such community interactions? What is the genomic inventory of deep microbial organisms? What are the effects of lateral gene transfer and the impact of mutations (incurred by cells that grow so slowly) on the evolution of cells in the deep subsurface? What is the role of phages in syntrophic interactions? Which genomic features support the adaptation and survival of microorganisms in the deep subsurface? Which DNA repair mechanisms do they apply? Why do cells in deep sediments (isolated) seem to be as little diverged as they are in the context of their 16S ribosomal RNA gene or other genes?

Another important aspect is how subsurface microbial communities affect processes in the surface systems and *vice versa*. For the future climate development it is crucial to know how deep microorganisms affect Earth's climate, considering the production of the greenhouse gas methane, especially when permafrost areas are thawing (climate feedback). Furthermore, in reverse, what is the effect of climate change on the deep biosphere with regard to hydrological changes and nutrient supply? These aspects include the general question to the role of the deep biosphere in the global carbon cycle.

Finally, subsurface microbial ecosystems are also of specific interest from a biotechnological point of view. The deep biosphere contains a large pool of genes and enzymes that are potentially useful for biotechnological applications. Microbial processes are able to support the exploitation of ores (bioleaching, biomining), clean fuel, and energy from tar sands and other unconventional fossil energy resources. Specific naturally occurring microbial consortia might also be helpful for the bioremediation of polluted sites.

*Upcoming ICDP projects for the integration of deep biosphere research.* Although ICDP has already recognized the importance of deep biosphere research in terrestrial drilling operations (Horsfield et al., 2007), only the ICDP Mallik Gas Hydrate Research Project (Fig. 1) and the Chesapeake Bay Drilling Project (impact crater) have had major deep biosphere components so far (Fig. 2), including contamination controls during core retrieval. There was some limited biogeochemical research in some lake sediment drilling projects as well: Lake Baikal, Potrok Aike Drilling (see Ariztegui et al., 2010 in this issue), and Lake El`gygytgyn. Although without contamination control, the paleoclimate drilling campaign in Lake Van, Turkey in 2010 also had a deep biosphere component.

In order to extend the number of projects with a deep biosphere component, the workshop identified a list of interesting upcoming ICDP projects where deep biosphere research might be added to already initiated projects. In particular, the ongoing ICDP lake drilling program appears to be an appropriate start to establish deep biosphere research in ICDP (for drilling locations see ICDP homepage, http://www.icdp-online.org). The sediments of lakes provide a unique opportunity to characterize and investigate the subsurface microbial communities in many different climatic zones of the Earth and, therefore, under different environmental conditions. There are three interesting upcoming lake projects in the near future (discussed below).

Lake Ohrid (Macedonia/Albania) is considered to be the oldest continuously existing lake in Europe (assessed age 1–10 Ma). It has a unique aquatic ecosystem with more than 200 described endemic species. The sedimentary successions in the central basin seem to reflect the complete history of the lake being an excellent archive for climate and volcanic activity in the central northern Mediterranean region.

The Dead Sea (Israel, West Bank, and Jordan) is the deepest hypersaline lake in the world. The deep basin of the Dead Sea contains a continuous sedimentary record of Pleistocene to Holocene age which forms an archive for climatic, seismic, and geomagnetic history of the east Mediterranean region.

Lake Issyk-Kul (Kyrgyzstan) contains a long climatic archive of this environmentally sensitive region in central Asia. During this drilling campaign a focus is laid on the time frame through the Pliocene into the late to middle Miocene. However, the recent political developments in Kyrgyzstan may prevent this project from taking place in the near future.

In addition to the lake program there is a series of other currently upcoming projects also of interest for deep biosphere research due to the specific characteristics of the study areas. Upcoming projects are Campi Flegrei Caldera, Italy (active volcanic area, high geothermal gradient), the Eger Rift, Czech Republic (area with high release of mantle $CO_2$ at the surface), and Collisional Orogeny in the Scandinavian Caledonides (COSC), Norway/Sweden (orogen dynamics, temperature gradient in the Caledonides, rock properties). More upcoming projects can be found at the ICDP homepage.

*Potential targets for a dedicated deep biosphere project within ICDP.* Another aim of the workshop was to identify potential targets for a dedicated terrestrial deep biosphere drilling campaign, forming the core of a future science proposal within the scope of ICDP. Terrestrial environments provide a broad range of different geological settings with their various associated deep microbial communities. Thus, only a selection of some potential targets for scientific deep biosphere drilling campaigns is presented here (see text box).

- Drilling outward and deeper from within a deep mine (e.g., at the Deep Underground Science and Engineering Laboratory (DUSEL)) for sampling and establishing of a natural laboratory to conduct *in situ* experiments
- Drilling at sites of active serpentinization and other locations where lithoautotrophic communities might occur or play a significant role
- Coring and monitoring of an active fault zone (Eger Rift) and establishment of a natural laboratory to investigate the role seismicity plays in subsurface life
- Drilling along a sequence of oil-bearing rocks to examine biodegradation gradients (e.g., Western Canada and Paris Basin) and with a possible industry connection
- Coring different sedimentary basins with different thermal gradients, different depositional conditions, and organic carbon composition and concentrations to investigate questions on the biogeography of the deep biosphere and the fate of the organic matter as a substrate for deep microbial life
- Drilling at locations where permafrost may be actively releasing biogenic methane (e.g., the high arctic of Canada and Siberia), with a possible link to IODP drilling campaigns, offshore permafrost
- Drilling coal seams to investigate the role of the deep biosphere in coal bed methane generation
- Drilling into an active mud volcano to investigate the role of microbial activity in the generation and degradation of hydrocarbons
- Examining the types of microbes, processes, and activities associated with locations where carbon capture and storage is being attempted (e.g., Columbia River basalts, U.S.A.)
- Drilling a borehole in the backyard of a science institute to establish an easily accessible natural laboratory to perform *in situ* experiments

Furthermore, it was highlighted that each project needs to consider and implement the best methods for collecting high quality samples for microbiological, biogeochemical, and geochemical analysis. This would also entail augmenting the methods book that will be used by future ICDP microbiology efforts. The projects should generally include basic measurements of the geology, geochemistry, mineralogy, etc. so that the environmental context can be understood for interpreting the microbiological ecosystems. Finally, the need for a central data base for the results of the ICDP projects was emphasized.

## Technical, Administrative, and Logistical Prerequisites

The fact that microbial cell abundance in subsurface environments is two to six orders of magnitude lower than at the surface makes the task of recovering uncontaminated supplies extremely difficult. Contamination control requires certain changes to standard drilling protocols, which can be achieved for a relatively small increase in cost when implemented already at an early planning stage. Also, handling and sampling procedures have to accommodate the special requirements to avoid alteration of the samples. Protocols like in IODP (Expedition 311 Scientists, 2006) have to be developed for ICDP drilling operations.

*Preventing and assessing contamination.* Due to the fact that basically all drilling operations use drilling fluids, contamination of cores through infiltration of drill fluid can only be minimized and not completely avoided. Uncontaminated samples are an absolute necessity for any subsequent analysis; therefore, contamination assessment is a crucial issue for geomicrobiological research in general.

In order to minimize contamination it is advisable to get involved in the planning of the drilling as early as possible, preferably as a Principal Investigator (PI), in order to have full control on the design of the operation. To achieve the best results in a cost effective way, it is also paramount to involve the drilling organization as early as possible. Any changes from standard drilling operations have to be taken into consideration early for the cost estimates; later changes can have dramatic effects on the overall budget. During the initial planning stage it is relatively easy to lay out the drilling operations according to geomicrobiology needs, even without compromising other research areas. Experience has shown that relatively few changes are necessary to minimize contamination of the samples. Most of these changes can be achieved relatively easily and for little extra cost if they are included in the planning at an early stage. Due to the great diversity of sediment/rock types to be drilled, the type of drilling equipment to be used, and other variables, there is no general rule on how to avoid contamination. Such an issue can only be addressed individually, given the specific circumstances.

During the drilling operation, standard microbiological procedures should be followed. While this is nothing new for a knowledgeable scientist, it may very well be so for the drilling staff. In order to ensure smooth drilling and sample handling, the drilling staff needs to be trained, and all procedures have to be discussed with and understood by them.

Still, there are some general issues that help to minimize contamination. Steam cleaning of all drilling equipment has proven to be a relatively cheap but effective way to reduce contamination by removing any foreign rock fragments and hydrocarbons from old pipe grease. A complete sterilization of the entire equipment is usually not necessary because the material will be contaminated again by the time it has traveled down the borehole. When sterilizing equipment, one should always ask the question whether it will be possible to get the sample into the sampler (core barrel, water sampler) without anything non-sterile getting in contact with the sample. Only in such cases does sterilization of equipment really make sense. There are situations, such as water sampling in deep aquifers, where sterilization of samplers may be useful and necessary, but such decisions have to be made on a case-by-case basis.

The choice of drilling technique is of major importance. In few cases (short holes, hard rocks), it is possible to drill without any drilling fluid and use air- or gas-lift techniques instead. High volumes of pressurized air or nitrogen are used in place of conventional drilling fluids to circulate the well bore clean of cuttings and to cool the drill bit. Air drilling can be used where formations are dry, i.e., when there is no influx of water into the hole. Also, normally the specific gravity of the drill mud prevents the hole from closing around the drill string. Boreholes have to be stable to use this technique due to the low density of the gas. So far, there is little experience with this technique for geomicrobiological purposes.

For softer sediments, hydraulic piston coring is the method of choice because this technique has shown to provide the least contaminated samples with regard to penetration of drilling fluid into the core. This is not surprising as the coring itself does not require any drilling fluids and relies solely on the force with which the cutting shoe is driven into the sediment, followed by rotary drilling around the core to extend the diameter of the hole and to push the bottom hole assembly further down. In IODP operations, the advanced piston coring tool (APC) is the prime tool for recovering soft sediments. Although this technique provides the highest quality cores and should, therefore, be carried out as deep as possible, it reaches its limitations in consolidated sediments.

The biggest problems are still the sediments of intermediate stiffness that are too hard for piston and too soft for rotary coring. IODP uses the extended core barrel tool (XCB), but the retrieved samples are often unsuitable for geomicrobiology research because of the high level of contamination and drilling induced disturbances in the core. In many cases the recovered cores consisted of pieces of sediment floating in a solidified mixture of drill mud and cuttings. Rotary drilling becomes the method of choice in consolidated sediments and hard rocks. When using rotary coring, contamination control becomes absolutely crucial, because this technique requires drill fluids and, unlike situations with the APC tool, the core is in direct contact with the rotating drill head. Due to the high pressure of the drill fluid coming out of the drill bit, the rock can be saturated with drill mud several centimeters ahead of the bit.

Drilling should always be carried out with liners to protect the drilled core from further contamination and to ease later handling. Still there will always be some drill mud in the gap between the liner and the drill core, and this mud can seep inwards and contaminate the interior of the core. Additionally, natural or drilling-induced fractures provide pathways through which the mud may enter the core.

Careful adjustment of the drilling conditions, rapid evaluation of the quality of the recovered core material, and, if necessary, changes to the drilling protocol can help to minimize contamination, but some degree of contamination may be expected for all cores collected by rotary drilling. Still, cores suitable for geomicrobiological research can be obtained by this technique.

The composition of the drill fluid has to be monitored carefully; all components of the drill fluids, including the water, should be checked for possible contaminants prior to drilling. The high density of the drill mud is achieved through the addition of clays, which have considerable differences in the microbial load. There is anecdotal evidence that synthetic clays usually contain fewer microbial cells than natural ones, but so far there is no systematic study about the microbial load of different clays. If possible, organic additives (thickeners, emulsifiers, stabilizers, etc.) should be limited to an absolute minimum because they represent a nutrient source for the microbes and can thereby enhance microbial activity. Hydrocarbon-based additives should be avoided at any cost as they interfere with most organic geochemical analyses.

A careful evaluation of all materials during the early planning stage can, therefore, significantly reduce the potential for contamination. Independent of the drilling technique and the composition of the drill mud, some contamination will always occur; therefore, contamination has to be assessed, preferably by multiple techniques.

The most common technique for contamination assessment is the use of fluorescent microspheres. These particles are available in a wide range of sizes (0.5 µm diameter is most common for contamination assessment). Microspheres have the advantage that they can be easily detected by fluorescence microscopy. Having a density very close to 1 g $cc^{-1}$, microspheres can be easily separated from the sample by density centrifugation on a cushion of sodium chloride solution. The disadvantage of microspheres is their price, which can add significantly to the total cost of a project.

There are two different ways to apply the microspheres. For hydraulic piston coring the easiest way is to attach small bags filled with spheres to the inner front of the core. As soon as the sediment enters the core barrel, the bag is ripped and the microspheres mix with the drilling fluid and eventually infiltrate the core. Using this technique the concentration of spheres in the mud is not constant and can only roughly be estimated; therefore, it is difficult to assess precisely how much drill fluid per volume of sediment has to enter the core in order to be detected by this technique. Still, this technique has been used for many years in IODP operations with very reliable results. Another way to apply microspheres is to add them directly to the drill mud. In cases where only a few depth intervals are being cored for geomicrobiological analysis, they can be added with a peristaltic pump into the intake of the mud pump. This way, the amount of microspheres can be limited to an absolute minimum. In cases where many depths are being cored, the entire volume of drill mud has to be amended with microspheres. Depending on the well depth and the required volume of drill mud, this approach may quickly reach cost limits. In order to detect sufficiently small concentrations of drill mud in the core, the concentration of microspheres should be at least around 1000 $\mu L^{-1}$. Depending on the diameter of the hole and the target depth, the volume of drill mud can vary between single and tens of cubic meters or even more. Microspheres are removed from the mud by various processes (Kallmeyer et al., 2006) and have to be added in regular intervals. Also, large volumes of drill mud can get lost in fractures and have to be replaced by fresh mud, requiring additional addition of microspheres. All these processes have to be taken into account when calculating the number of necessary microspheres.

The addition of known and easily identifiable microorganisms would be an alternative type of particulate tracers. However, this approach will possibly cause major legal problems in many if not most areas.

Solute tracers may offer a viable alternative to added allochthonous microbes and microspheres. In IODP operations perfluorocarbon tracer (perfluoromethylcyclohexane, PFT) has been used on several occasions with good results, although the data may differ somewhat from those obtained with microspheres (Smith et al., 2000a, 2000b). PFT is much cheaper than microspheres, but its detection requires a gas chromatograph, which may cause logistical problems on the drill site. Although this technique is very sensitive, possible incompatibilities with the drill mud matrix have to be evaluated prior to drilling. Also, the samples have to be taken quickly after retrieval of the core, due to the high volatility of PFT.

During the ICDP Chesapeake Bay impact drilling, halon was used as a tracer. Although the results were satisfactory, this technique will most probably not be used in future drilling operations because of the decreasing availability of Halon as it becomes banned in many countries due to its deleterious effects on the ozone layer.

Fluorescent dyes can be detected by fluorometry, which is a relatively easy and robust technique, allowing for analysis right at the drill site. This may be very helpful in cases where unforeseen changes in drilling operations become necessary, and possible influences on the quality of the recovered material need to be evaluated on the spot. A variety of fluorescent dyes have been used successfully in various operations: rhodamine WT, uranine, lissamine FF, fluorescine, amino G acid (7-Amino-1,3-naphthalenedisulfonic acid). However, quenching of the fluorescence signal due to coloration of the sample may complicate the exact quantification of the infiltration of drill mud into the core.

The level of contamination can vary on a small scale, not just in terms of distance from the outside of the core but also between different sample depths. The drill mud may have infiltrated the core along small cracks, which are not visible upon manual inspection of the core; therefore, even if adjacent contamination controls are "clean", that may not guarantee an uncontaminated sample. Ideally, contamination should be assessed on the sample being analyzed. Redundancy of contamination control is important; at least two different methods should be used in order to ensure good contamination control under all circumstances.

*Sampling and sample storage.* After the cores are retrieved, sample collection is the next major step. The contaminated outer part of the core has to be removed. Only the uncontaminated inner part can be used for geomicrobiological research (inner coring technique). How much of the outer part needs to be removed and how much uncontaminated material actually becomes available for analysis have to be determined individually. If anaerobic conditions are required for the sample material, sampling has to be conducted in an anaerobic glove box.

Sampling techniques have to be adjusted according to lithology. In soft sediments subsampling can be done with cut-off syringes, whereas in hard sediments the center subcore has to be retrieved by drilling. Cut-off plastic syringes are cheap and can be prepared in large quantities prior to drilling. Metal core drills for hard sediments are much more expensive and usually not available in the same quantities as syringes. The effort in time and manpower of recycling these drills (retrieval of sample, cleaning, sterilization) has to be taken into account when planning the amount of samples that can be processed in a given time.

Sample preservation is another important issue. There are different approaches currently being used, depending on the parameter to be preserved. The standard technique for storage of cell count samples from soft sediment is a solution of similar salinity with formalin. A common method for general geochemical sampling is to put the whole sediment into gas-tight bags flushed with nitrogen and/or containing an oxygen scrubber. Such samples have proven to be a good option for further subsampling in the laboratory.

Another option would be gel preservation. The sample is coated with an antimicrobial gel that prevents surface growth and limits gas exchange. In some cases special waxes with a low melting point have been used to coat samples. However, the application of this technique has so far been limited to samples for physical and chemical analysis, not microbiology. There are no data available whether these waxes give off any volatile compounds that could potentially be used as a carbon source by microbes.

Pore water should be extracted as quickly as possible to avoid alteration during storage. Squeezing yields the highest amounts of pore water but destroys the sediment structure. Rhizon samplers are not as effective but leave the sediment structure intact, thereby allowing the use of the core for other purposes. However, Rhizon samplers apply a vacuum to the retrieved pore water, thus causing the loss of gases, especially $CO_2$. This loss in $CO_2$ will inevitably alter the pH of the sample. Although not very efficient, centrifugation can be the method of choice for highly porous and soft sediments.

Samples should be stored according to the parameter to be analyzed. Storage at 4°C is preferred for turnover rate measurements and cell counting. For molecular analysis, storage at -20°C may not be cold enough to stop all degradation processes. The best method is still storage in liquid nitrogen, because at that temperature all degradation processes are stopped and oxidation is completely avoided. However, liquid nitrogen may not be available in remote locations, and transport may also be an issue, although with special containers samples can even be sent by airfreight in liquid nitrogen.

*Integration of a standard minimum sampling scheme.* Compared to the marine realm, terrestrial subsurface microbiology is lagging behind by many years. One of the main reasons for this is the lack of available samples. A minimum sampling scheme that could become a compulsory standard component of all ICDP drilling operations could help to overcome this lack of material. Such a minimum sampling scheme would not interfere with other analyses and could be done with relatively little additional effort. Like in IODP, certain physical parameters should also be measured routinely in order to advance our understanding of subsurface biomass, activities, and habitability. These data would be extremely helpful not just for geomicrobiological research but for other fields as well. Routine measurements should include formation factor as well as downhole temperature and pressure. There have to be at least two different minimum sampling schemes, one for soft and one for hard sediments.

For soft sediments the minimum requirements would be:

- Pore water via Rhizon sampler, split into acidified and chilled aliquots. Such a sample cannot be used for quantification of dissolved inorganic carbon (DIC) or alkalinity due to loss of $CO_2$. For such measurements a squeezed sample would be preferable. In cases where only one technique can be applied, the Rhizon samplers are still preferable, unless the $CO_2$-sensitive parameters are of major interest.
- Cell count sample (2-cc syringe sample, stored in 2% formalin), in cases where no contamination control can be made, the sample should be taken from the absolute center of the core and as far away as possible from any visible cracks.
- Dissolved gases sample (2-cc syringe sample, stored in 10% NaOH)
- Elemental parameters (CHN sample): 2-cc sample, stored at -20°C or colder.
- A short whole round core or a large (60 cc) syringe frozen at -80°C for future molecular studies. The cost of such studies is declining rapidly, and the samples will be invaluable.

For hard material the minimum requirement would be a drilled subcore sample, stored in a gas-tight bag, flushed with nitrogen and/or equipped with an oxygen scrubber, stored at 4°C.

So far, subsurface microbiology in ICDP projects has mainly been done as “one-off” operations, with contamination control and sample handling protocols being developed individually for the specific projects. These individual approaches make it rather difficult to compare data from different projects. By making the minimum sampling schemes a standard part of ICDP operations, a much wider community could use these data.

*Data storage.* Storage of the logging data can be managed rather easily through the ICDP Operations Support Group (OSG), whereas storage of legacy samples is a much more complicated issue because there are no central storage facilities for ICDP cores. Although legacy samples form a valuable resource for future research, they also represent a great burden and cost factor. As this is an issue that is not just affecting geomicrobiology, it should be addressed on a larger scale.

*Drilling and mobile laboratory facilities.* ICDP drilling operations are much more diverse with regard to drilling equipment and work environment than at IODP, where the drill ships operate according to well-known standard procedures and provide a good working environment. Still, a large fraction of ICDP operations employs the same drilling equipment, namely the DOSECC rigs and, in the future, the INNOVA Rig as well. A test drilling operation was carried out with DOSECC’s Glad 800 Rig at Great Salt Lake, which allowed for equipment testing and, due to the vicinity of DOSECC headquarters, immediate refinement and modification of equipment in the workshop when necessary. There should also be the opportunity for a geomicrobiology test drill to develop and refine the required drilling protocols for biogeochemical and microbiological research. Such an operation should be science driven as opposed to being just a technical exercise, but the geologic setting has to be well known in order to avoid any problems due to unforeseen lithological changes. It would, therefore, be a good option to add such a test drill onto an already scheduled drilling operation. Whereas normal drilling operations are usually run to a rather tight schedule, it is important to allocate sufficient additional time and resources for the testing and not to squeeze this into the already tight schedule of the general project.

For geomicrobiological research, sample processing immediately after retrieval is important to avoid alteration of the samples. Sufficiently equipped laboratories are readily available on the IODP drill ships. This is much different for ICDP operations, where quite often they are located in remote areas with more complicated or impossible access to a suitable laboratory. One solution to this problem is the new BUGLab facility of the Helmholtz Centre Potsdam (GFZ) German Research Centre for Geosciences (Fig. 3). The laboratory is composed of two portable standard 20-ft containers, which can be combined if necessary. Due to their modular structure, the BUGLab containers can be equipped according to the specific requirements of the planned work, allowing the processing of microbiological and biogeochemical samples, on-site analysis of biologically significant transient properties, and on-site analysis of chemical and physical properties that are being useful to guide microbiological and biogeochemical sampling strategies.

Figure 3. The GFZ BUGLab container is a mobile field laboratory for geomicrobiological and biogeochemical research. The container can be deployed in a wide range of both marine and terrestrial settings, from polar to tropical environments.

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Fig. 1 – ICDP
Fig. 3 – Kai Mangelsdorf, GFZ Potsdam

# The MoHole: A Crustal Journey and Mantle Quest, Workshop in Kanazawa, Japan, 3–5 June 2010

by Benoît Ildefonse, Natsue Abe, Donna K. Blackman, J. Pablo Canales, Yoshio Isozaki, Shuichi Kodaira, Greg Myers, Kentaro Nakamura, Mladen Nedimovic, Alexander C. Skinner, Nobukazu Seama, Eiichi Takazawa, Damon A.H. Teagle, Masako Tominaga, Susumu Umino, Douglas S. Wilson, and Masaoki Yamao

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## Introduction

Drilling an ultra-deep hole in an intact portion of oceanic lithosphere, through the crust to the Mohorovičić discontinuity (the 'Moho'), and into the uppermost mantle is a long-standing ambition of scientific ocean drilling (Bascom, 1961; Shor, 1985; Ildefonse et al., 2007). It remains essential to answer fundamental questions about the dynamics of the Earth and global elemental cycles. The global system of mid-ocean ridges and the new oceanic lithosphere formed at these spreading centers are the principal pathways for energy and mass exchange between the Earth's interior, hydrosphere, and biosphere. Bio-geochemical reactions between the oceans and oceanic crust continue from ridge to subduction zone, and the physical and chemical changes to the ocean lithosphere provide inventories of these thermal, chemical, and biological exchanges.

The 2010 MoHole workshop in Kanazawa, Japan followed from several recent scientific planning meetings on ocean lithosphere drilling, in particular the Mission Moho Workshop in 2006 (Christie et al., 2006; Ildefonse et al., 2007) and the "Melting, Magma, Fluids and Life" meeting in 2009 (Teagle et al., 2009). Those previous meetings reached a consensus that a deep hole through a complete section of fast-spread ocean crust is a renewed priority for the ocean lithosphere community. The scientific rationale for drilling a MoHole in fast-spread crust was developed in the workshop reports (available online) and most thoroughly articulated in the 2007 IODP Mission Moho drilling proposal (IODP Prop 719MP; www.missionmoho.org).

The 2010 MoHole workshop had two interconnected objectives, which have been discussed jointly between ocean lithosphere specialists, marine geophysicists, and engineers:

- to initiate a roadmap for technology development and the project implementation plan that are necessary to achieve the deep drilling objectives of the MoHole project,
- to identify potential MoHole sites in the Pacific (i.e., in fast-spread crust), where the scientific community will focus geophysical site survey efforts over the next few years.

Selecting drilling sites is essential to identify the range of water depths, drilling target depths, and temperatures that we anticipate, and to better define the technology required to be developed and implemented to drill, sample, and geophysically log the MoHole.

## A Brief Summary of the Scientific Rationale for the MoHole

The Moho is the fundamental seismic boundary within the upper part of our planet, yet we have little knowledge of its geological meaning. New deep drilling technology now make it possible to fulfill scientists' long-term aspirations to drill completely through intact oceanic crust, through the seismically defined Moho and then a significant distance (~500 m) into the upper mantle. Our scientific goals (Fig. 1; Christie et al., 2006; Ildefonse et al., 2007; Teagle et al., 2009) can be divided into the following principal tightly interconnected threads.

- What physical properties cause the Mohorovičić discontinuity, and what is the geological nature of this boundary zone?
- How is the (lower) oceanic crust formed at the mid-ocean ridges, and what processes influence its subsequent evolution? What are the geophysical signatures of these magmatic, tectonic, hydrothermal, biogeochemical, and chemical processes?
- What can we infer about the global composition of the oceanic crust, and what are the magnitudes of interactions with the oceans and biology and their influence on global chemical cycles?
- What are the limits of life, and the factors controlling these limits? How do the biological community compositions change with depth and the evolving physical and chemical environments through the oceanic crust?
- What is the physical and chemical nature of the uppermost mantle, and how does it relate to the overlying magmatic crust?

### *The Mohorovičić Discontinuity*

In the oceans, the Moho is commonly a bright seismic reflector at 5–8 km depth, marking a step change to seismic

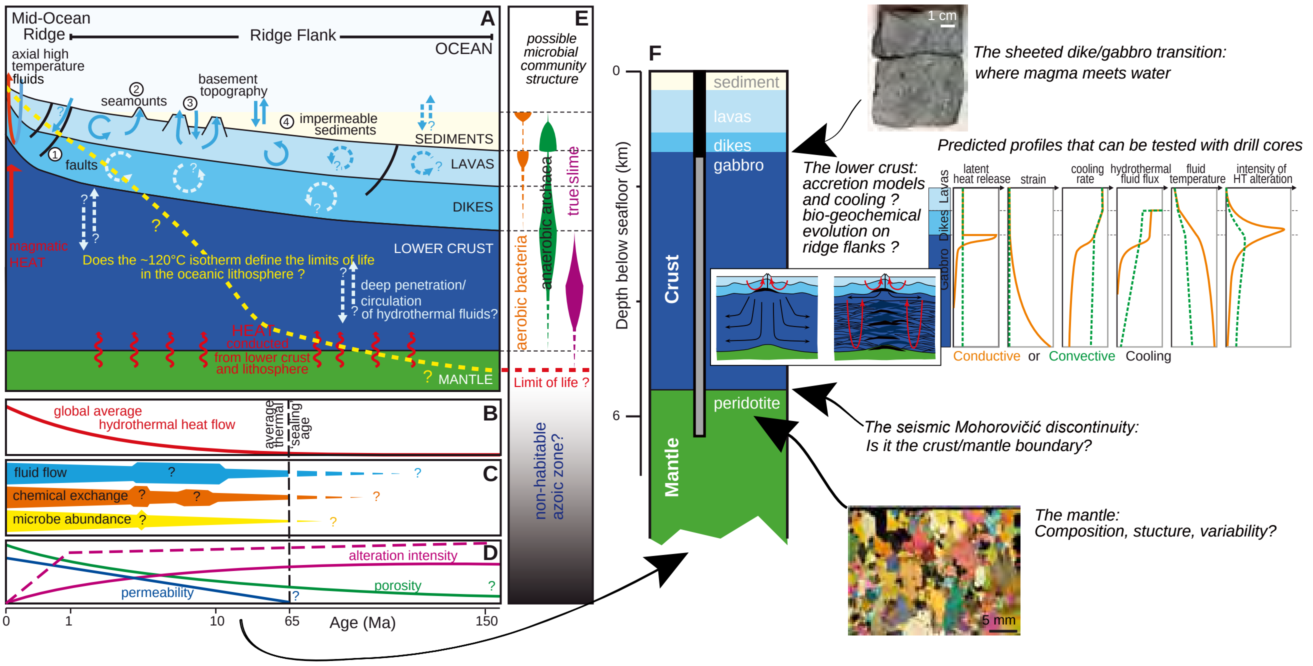


Figure 1. [A] Schematic architecture of a mid-ocean ridge flank (not to scale), illustrating parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as faults, seamounts, basement topography, and impermeable sediments, which isolate the crust from the oceans. Arrows indicate heat (red) and fluid (blue) flow. [B] The calculated global hydrothermal heat flow anomaly decreases to zero, on average, by 65 Ma. [C] The effects of parameters such as basement topography and sediment thickness on the intensity and relative cessations of fluid flow, chemical exchange, and microbial activity remain undetermined. [D] Evolution of porosity, permeability, and alteration intensity with age. [E] Hypothetical change in microbial community structure with the depth limit of life increases with crustal age. [F] Schematic cross-section of fast-spread crust with anticipated MoHole penetration. The thicknesses of sediment, lavas, and sheeted dike complex are taken from ODP/IODP Hole 1256D (Teagle et al., 2006). Top photograph: sheeted dike complex/gabbro contact in Hole 1256D. Predicted end-member physical/chemical profiles in the crust: figure from Rosalind Coggon; Lower crust accretion models: after Korenaga and Kelemen (1998). Bottom photomicrograph: mantle peridotite xenolith from French Polynesia (Tommasi et al., 2004).

P-wave velocities (Vp) in excess of 8 km $s^{-1}$. It is generally assumed that the Moho also represents the boundary between mafic igneous rocks (crystallized from magmas that form the crust) and residual peridotites of the upper mantle. However, this interpretation has never been tested, and there are geologically valid scenarios where the Moho might delineate the boundary between mafic and ultramafic cumulate rocks within the crust, or exist below serpentinized peridotites that were previously part of the mantle. Observations and sampling of the Moho, the petrological crust-mantle boundary, and the rocks of the upper mantle are fundamental to understanding the geodynamics and chemical differentiation of our planet. A foremost goal is to reconcile geophysical imaging of the Moho with direct geological observations of cores and downhole measurements (e.g., is the Moho in our study region a sharp compositional boundary or a transition zone of significant thickness?).

## Formation of the Lower Crust

On the road to the Moho, we will make paradigm-testing observations of the lower oceanic crust and the deep magmatic, tectonic, and hydrothermal processes that occur at the mid-ocean ridges (Fig. 1). Our principal target will be intact ocean crust formed at a fast-spreading ridge, which should be relatively laterally uniform, and where we have well-developed theoretical models of crustal accretion that can be tested by drilling. Is the lower oceanic crust formed from the subsidence of a high-level magma chamber, or are there multiple melt bodies at different levels within the oceanic crust (or upper mantle) at fast-spreading ridges?

Magnetic stripes document the history of ocean crust formation and are the very basis of plate tectonic theory, yet we have little information on what contribution the lower crust has to this fundamental signature. Similarly, seismic profiling remains the key tool for investigating the deep crust, but these regional scale measurements have never been calibrated against core or *in situ* measurements. It remains challenging to confidently develop geological interpretations from geophysical measurement of the oceanic crust.

## Composition and Hydration of the Ocean Crust

A full penetration will provide the first direct estimate of the bulk composition of ocean crust critical for Earth differentiation models. How deeply do seawater-derived hydrothermal fluids penetrate, and how efficient is hydrothermal circulation at heat extraction and chemical alteration (Fig. 1)? Is fluid flow channeled by major faults, or is it more pervasive? The knowledge of modes of penetration of the hydrothermal fluids, and of the extent of their interactions with the lithosphere, is required to estimate chemical exchanges with the oceans, as well as to assess the volume and composition of materials transferred to the mantle via subduction.

## Limits and Controlling Factors of Life

Understanding the limits of life (Fig. 1), and the factors controlling these limits, is one of the most fundamental goals of geo- and biosciences essential for understanding the origin, evolution, distribution, and future of life on Earth as well as celestial bodies. To date, the limits of life even on our own planet remain poorly defined. The MoHole project provides a unique opportunity to address these limits in the oceanic lithosphere that covers ~60% of our planet. Numerous factors may control the limits of life, such as temperature, water activity, salinity, pH, and energy and carbon sources. Among these, temperature plays a key role, because organisms cannot survive beyond as yet a poorly known temperature threshold (~110–120°C?). The ability of seawater to penetrate into the deep crust or mantle and be available for microorganisms (e.g., minimum pore space) will also have a strong impact on the distribution of living organisms.

## Physical and Chemical Nature of the Upper Mantle

Direct observations of the mantle will document how magmas are focused from a broad melting region to a narrow zone of crustal accretion beneath mid-ocean ridges. Measurements across the Moho will quantify the tectonic coupling between the crust and mantle. We presently have little knowledge of the composition and physical state of *in situ* convecting mantle at the ridge axis. A few kilograms of fresh residual peridotite from beneath intact oceanic crust would provide a wealth of new information comparable to the treasure trove obtained from the Apollo lunar samples.

## Geophysical Characteristics of the Mohole Project Area

The criteria for best possible deep crustal penetration sites were reformulated during this workshop. The selected target would ideally meet all of the following scientific requirements:

a) Crust formed at fast-spreading rate (>40 mm $yr^{-1}$ half rate).
b) Simple tectonic setting with very low-relief seafloor and smooth basement relief; away from fracture zones, propagator pseudo-faults, relict overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism. Connection to the host plate active constructive and destructive boundaries would provide important scientific information.
c) Crustal seismic velocity structure should not be anomalous relative to current understanding of "normal" fast-spread Pacific crust, indicative of layered structure.
d) A sharp, strong, single-reflection Moho imaged with Multi-Channel Seismic (MCS) techniques.
e) A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn).
f) A clear upper mantle seismic anisotropy.
g) A crust formed at an original latitude greater than ±15°.
h) A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole.

Satisfying requirements for points a–e is essential for success. More flexibility is allowed in meeting points f–h, which are highly desirable but not essential. Several technological constraints limit the range of potential sites:

- Technology for re-circulating drilling mud (riser or alternative; see next section) is currently untested at water depths greater than 3000 m.
- Prior scientific ocean drilling experience is mostly limited to temperatures less than 200°C. Temperatures higher than ~250°C will may limit choices of drill bits and logging tools, may decrease core recovery, and may increase risk of hole failure, or require substantial re-design of drilling equipment. Based on plate cooling models, crust older than ~15–20 Ma should meet this requirement at Moho depths (Fig. 2).
- Thickness of the crustal section above Moho must be at least a few hundred meters less than the maximum penetration/logging/recovery depth of the drilling system to allow significant penetration in mantle peridotites.
- Target area should be in a region with good weather conditions at least eight months out of the year, with calm seas and gentle ocean bottom currents.

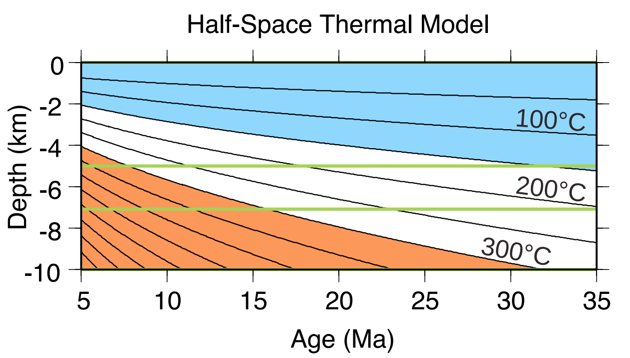


Figure 2. Predicted temperature as a function of age and depth (half-space thermal model by D. Wilson). Thermal diffusivity is $6x10^{-7}$ $m^2s^{-1}$, the initial mantle temperature is 1340°C, the surface temperature is 0°C. At 6 km, cooling below 200°C occurs after 25 Ma.

- Sediment thickness should be greater than 50 m to support possible riser hardware and other seafloor infrastructure (re-entry cones/uppermost casing strings).
- Targeted area should be close (less than ~1000 km) to major port facilities for logistical practicalities.

## Potential Sites

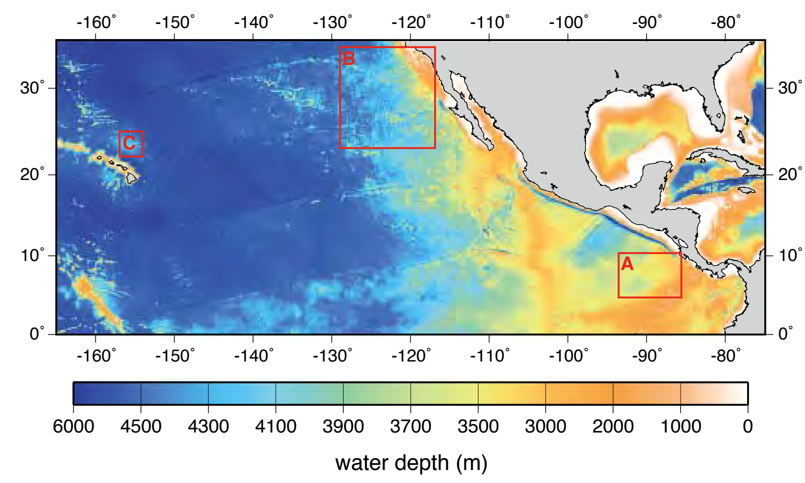


Figure 3. Bathymetric map showing the three selected areas for large-scale MoHole site survey: [A] Cocos plate region, [B] off Southern/Baja California region, [C] off Hawaii region.

Based on the scientific requirements and technological constraints described above, the workshop participants focused discussions on three areas in the Pacific Basin: Cocos Plate, off Southern and Baja California, and off Hawaii (Table 1; Fig. 3). One of the most important issues to take into consideration is the trade-off between seafloor depth and temperature at Moho depths. Most ocean seafloor subsides below 4000 m by ~25 Ma, whereas at Moho depths of 5–7 km temperatures of 200˚C or less are expected for crustal ages of 17–35 Ma (Fig. 2). The respective advantages and disadvantages of the three selected areas are listed in the full workshop report (available online at http://campanian.iodp.org/MoHole/).

The *Cocos Plate region* (Site 1256 area, Fig. 3A) encompasses a section of the Cocos Plate off Central America (from Guatemala to northern Costa Rica) with lithospheric ages between 15 Ma and 25 Ma. At its western limit on 15-Ma crust, this area includes the Ocean Drilling Program (ODP) Hole 1256D (Wilson et al., 2006; Teagle et al., 2006), a site of ongoing Integrated Ocean Drilling Program (IODP) deep drilling into intact ocean crust. MCS (Hallenborg et al., 2003; Wilson et al., 2003) and wide-angle ocean bottom seismometer (OBS) data exist for the 15–17 Ma area in the vicinity of Site 1256. This region sits in superfast crust (half-spreading rate 110 m yr$^{-1}$), within a corridor that includes a complete tectonic plate life cycle, making it an excellent candidate for understanding ocean crust evolution from a spreading center to subduction. Structure of the crust within this area can be directly related to processes occurring at the modern East Pacific Rise and the Central American subduction zone.

The *off Southern/Baja California region* (Fig. 3B) encompasses a section of the eastern Pacific Plate at ~20˚–33˚N and ~130˚–118˚W. Crustal ages are ~20–35 Ma. Very little

Table 1. Principal characteristics of possible candidate sites for the MoHole project.

| Candidate Site | Location | Half-Spreading Rate (mm yr$^{-1}$) | Crustal Age (Ma) | Inferred Moho-T (°C) | Water Depth (m) | Sediment Thickness (m) | Crustal Thickness (km) | Total Length to the Moho (km) | Original Latitude |
|---|---|---|---|---|---|---|---|---|---|
| Cocos (Site 1256) | 6.7°N, 91.9°W | 110 | 15 | >250 | 3646 | 250 | 5,5 | 8.7–9.2 | Near equator |
| Cocos (Site 844) | 8°N, 90.5°W | 100 | 17 | >250 | 3414 | 290 | 5,5? | 8.7–9.2? | Near equator |
| Cocos | 8.7°N, 89.5°W | 100 | 19 | ~250 | ~3400 | ~300 | 5,5? | 8.7–9.2? | Near equator |
| off S/Baja California (Deep Tow Site) | 31°–33°N, 125°–127°W | 60 | 30–27 | <200 | 4300–4500 | ~100 | ~5.5? | ~10? | ~30–33 |
| off S/Baja California | 28°–29°N, 123°–125°W | 50 | 27–22 | ~200 | 4200–4400 | ~100 | ? | ? | ~28 |
| off S/Baja California | 25°–26°N, 120°–122°W | 60 | 27–22 | ~200 | 3900–4300 | ~80 | ? | ? | ~30 |
| off S/Baja California | 30.5°–31°N, 121°W | 45 | 20–22 | ~250 | 2700–4100 | ~130 | ? | ? | ~25 |
| Hawaii | 22.9°–23.7°N, 154.9°–155.8°W | 35–40 | 79–81 | ~150 | 4050–4300 | ~200 | ~6? | 10–10.5? | Near equator |
| Hawaii | 23.5°–23.9°W, 154.5°–154.8°W | 35–40 | 78 | ~150 | 4300–4500 | ~200 | ~6? | 10–10.5? | Near equator |

modern geophysical information exists from this region. The best-studied area is in the northernmost part off San Diego, the "Deep Tow" site at 32°25'N, 125°45'W (31–32 Ma; Luyendyk, 1970). Historical data there include deep-tow sidescan and bathymetry, 3.5 kHz profiler, magnetics, and single-channel seismics.

The *off Hawaii region* is located north of Oahu in the flexural arch, where water depths are 4000–4300 m. The crust is ~80 Ma and was formed at an intermediate half-spreading rate of 35–40 mm $yr^{-1}$. This site offers the lowest temperature at Moho depth (~100°C–150°C), but crustal structure is potentially affected by hotspot volcanism (underplating and/or crustal intrusions), and its significantly older age makes it difficult to relate geochemical changes to modern ocean chemistry or conditions.

### Geophysical Surveys: Finding the Right Project Area

The existing geophysical data at all potential sites are not sufficient to identify a clear MoHole Project target area. Consensus at the workshop was that the priority of the community should be directed toward conducting large-scale seismic surveys in the three selected regions, which will lead to the identification of a MoHole target that best satisfies the requirements stated above. These surveys should collect spatially coincident MCS data, wide-angle OBS data, multi-beam bathymetry and gravity. Heat flow and magnetic anomaly data will be useful and should be collected. The characteristics of the required seismic surveys are listed in the full workshop report. JAMSTEC will dedicate three months of science ship time in 2011 for large-scale surveys. There was a consensus that the first survey should be in the off Southern/Baja California region, because so little is known in this area (where depth/age/logistical criteria are viable). Baseline reconnaissance seismic data are urgently required to assess whether this area can possibly meet the scientific requirements. Two additional factors contributed to the choice of this region as short-term priority for initial reconnaissance: crustal ages are greater than near Site 1256 (so temperatures are expected to be cooler), and the existing data suggest that Moho in the Site 1256 area may not be associated with a simple, continuous, strong reflector.

After an appropriate drilling target has been identified, the community should conduct detailed seismic surveys in the vicinity of the specific target, including 3-D multi-streamer MCS and OBS surveys for accurate and geometrically correct imaging of intracrustal reflectors (faults, sills, etc.) and Moho, and to assess crustal structure and thickness variability, and upper mantle velocity structure/anisotropy.

The scope and costs of the surveys required for this project are too large to be undertaken by a single nation or funding agency, hence international collaboration is essential.

## Technology Development and Operations

The MoHole initiative is arguably at the point where the framework for the operations can be constructed, since the technology to drill such a hole exists or at least has been shown to be feasible. The technology selection and required engineering development will be key components for the success of the MoHole project. It is important to identify potential issues in drilling and coring engineering from the past and ongoing ocean drilling expeditions, and to find solutions to overcome the problems encountered. The engineering efforts must be directed to ensure that the scientific goals of the MoHole project are achieved. Technology selection process and planning for the key engineering developments should be launched as soon as possible in conjunction with site-survey efforts. To do so, establishing a realistic roadmap, which includes project scoping, development and testing elements all controlled by proper project management, is imperative. All MoHole target sites are located in ultra-deep water of ~4000-m water depth or beyond, and the drilling depth to achieve the MoHole objectives is estimated to extend more than 6000 m below the seafloor. To drill such an ultra-deep borehole, the provision for continuous mud circulation is a top priority technology requirement. Other major areas requiring engineering consideration include logging and coring in high temperature environment, drill bits (specifically designed for abrasive, hard rocks) and drill string (high tensile strength), drilling mud (developed for high temperature environment), and casing/cementing materials and strategies (specifically designed, ideally to the bottom of the hole).

A promising candidate technology for drilling the MoHole is riser drilling, which provides a conduit for the mud to be returned to the vessel for cleaning, evaluation, and recirculation. The D/V *Chikyu* is currently equipped with a deep riser system with a maximum rated water depth of 2500 m. Significant engineering development is required to prepare the D/V *Chikyu* for riser service in water depths ≥4000 m. In addition to riser drilling, several other technologies are being considered to drill safely and efficiently to the target depth, including Surface Blow Out Preventer (BOP) with slim riser pipe (casing pipe) and Shut In Device (SID), or Riserless Mud Recovery (RMR; Myers, 2008) with mud circulation pump and mud return line. The lithologies intersected by the borehole drilled to Moho depths are unequivocally expected to be free from overpressures, hydrocarbons, or other geohazards. However, future regulatory changes may require the use of blow-out prevention in mud circulation systems. Hence, although a BOP will likely not be needed for well control, the use of a BOP will be considered by the MoHole planning group.

Drilling the MoHole will be a challenging enterprise requiring years of detailed preparation, planning, and engineering. Operationally, major challenges will be associated with collecting the cored material, making the *in situ* measurements, installing casing, and keeping the borehole open for successive episodes of deepening in a multiyear, multiphase operation. To gear up for the operations, all issues related to drilling, casing, coring, and logging must be adequately explored and included in a comprehensive and complete operation plan, as soon as the site characteristics are known. Key elements of the drilling/coring/downhole measurements were listed during the workshop (see full workshop report). The well design of the primary site may require data from a pilot hole, to properly evaluate parameters such as mud weights and casing set points. A pilot hole may be either a separate hole or simply a pilot section of the main hole. Drilling engineering data from a pilot section will be critical in managing the pressure, temperatures, and stress within the borehole.

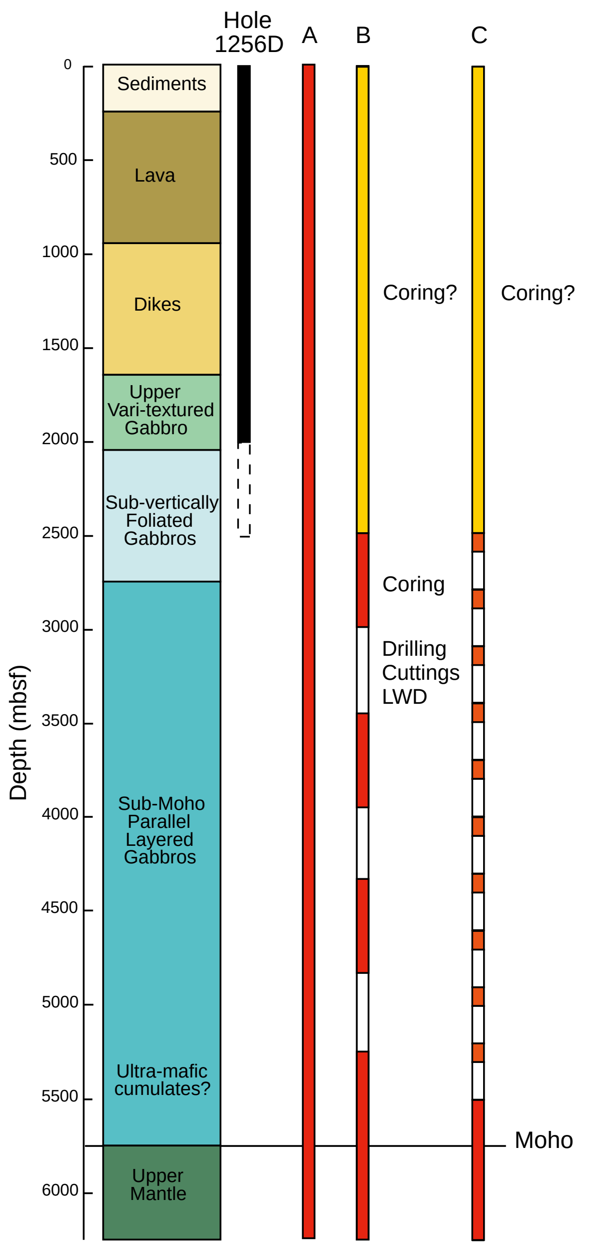


Figure 4. Technology and financial constraints willing, continuous coring all the way to the Moho and then a significant distance (~500 m) into the uppermost mantle [A] would be the best approach to achieve the scientific goals of this project. However, approaches that mix spot coring ([B] long coring of key sections or [C] 10-m coring before bit change every 50 m) with continuous wireline coring may need to be considered. Significant lengths of continuous cores across major lithologic and geophysical transitions are mandatory to answer the fundamental scientific questions.

After completion of drilling, coring, and borehole logging, the MoHole should be used for further experiments, including vertical seismic profiles (VSP), and long-term monitoring. Given the extreme borehole depth to be drilled, at least two offset VSPs are ideally required, one at the estimated halfway point of the well and perhaps one at final depth. Instrumenting the MoHole will eventually become a key, second-stage goal. Hence, the sub-sea equipment and borehole must be constructed to accommodate observatory science (e.g., fluid monitoring, microbiology incubation experiments). This implies ROV access to the wellhead and the ability to access the borehole through a BOP or SID.

## Keys for Success

The keys for a successful MoHole project, as identified during the workshop, include scientific (essentially sampling strategy) considerations, as well as technology development, industry engagement, and public engagement through outreach activities and education. The MoHole project will be one of the largest scientific endeavors in Earth science history, and this challenge should provide precious opportunities to a diversity of scientists, engineers and technologists. One of the keys to success will be the sharing of the opportunities and achievements across a broad spectrum of Earth and life scientists.

The size and duration (ten years or more) of the MoHole project will require an appropriately supported, centralized science operations and engineering management group to oversee the successful initiation and completion of the project. This international group will be key to success and should be created as early as feasible. The envisioned, ideal timeline for the MoHole project is to complete prospective 2-D site survey (including data analysis) in ~2014, choose the MoHole site and conduct 3-D site survey in ~2015, start preparing operations in ~2015-2016, start drilling in ~2018, and reach the mantle in ~2022.

### *Scientific Coring, Sampling, and Measurements*

Many of our primary scientific goals will require continuous core samples. To be regarded as successful, the MoHole project must at least return the following (see also Fig. 4):

- Continuous core, including samples of all boundaries, across the region identified by seismic imaging as the Moho, and the lithologic transition from cumulate magmatic rocks to residual peridotites (these may or may not be the same target)

- Continuous coring of the lower 500 m of the mafic and ultramafic cumulate rocks in the oceanic crust
- Continuous coring of 500 m of peridotites and associated lithologies in the uppermost mantle below the Moho
- Sufficient cores from intervals of the lower oceanic crust to test models of crustal accretion and melt movement, to resolve the geometry and intensity of hydrothermal circulation, and to document the limits and activity of the deep microbial biosphere
- A continuous, comprehensive suite of geophysical logs (wireline, Logging While Drilling/Coring) and borehole experiments to measure *in situ* physical properties, to acquire borehole images, and to identify key geophysical and lithologic regions and transitions (e.g., Layer 2-3 boundary, the Moho) throughout the ocean crust and into the upper mantle.

Due to the expected relatively coarse grain size of the rocks to be encountered in the MoHole and the fine scales of expected lithologic/geochemical variation, it is anticipated that lithological records provided by mud/chip logging will be insufficient to address the scientific questions posed. However, a continuous series of mud, cuttings, and gas logs will provide useful supplementary information in areas of poor or no core recovery, and should be routine throughout the experiment. In addition to sampling and analyzing rocks, measurements of temperature and chemical compositions of fluids are required, together with biological analyses such as cell counting and DNA/RNA analyses.

## Drilling Technology and Industry Engagement

Technologies that are applicable to the MoHole project are now being developed within the oil and gas industry. These were presented at the workshop by industry representatives. Conversely, some of the required technologies are very specific to scientific drilling, such as logging and coring at high temperatures (e.g., the IDDP project, Skinner et al., 2010) or drilling the hard crustal and mantle rocks. Development of such technologies will be a primary key for success, but to achieve this it may be necessary to complement IODP financial support with external funding.

As the oil and gas industry conducts operations in increasingly deep water, important keys for success will be continuous collaboration with industry and introduction of new technologies to the MoHole project where applicable. It will be necessary to establish a strategy to engage the industry in the project, exchange personnel, and plan joint development work. This can occur at several levels, including i) continuing *ad hoc* collaboration, through inviting oil and gas industry representatives to participate in planning activities and community workshops, ii) contracting services from planning to execution, and iii) participation of engineers and scientists engaged in the MoHole project to industry workshops, symposiums, and technology development forums.

## Public Engagement, Outreach, and Education

Another key component of the success of a Mohole project will be to improve public support and understanding of the scientific goals and excitement of the project. Engaging the public through outreach and education activities, as well as being pro-active in advertising the project to the wider scientific community and engaging new groups of scientists, should be integral parts of the activities carried out by the MoHole project scoping group, under the umbrella of IODP and future international collaboration for scientific ocean drilling. One tool to be implemented rapidly, as soon as scoping activities commence, is a dedicated, dynamic and engaging MoHole web page.

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## Related Web Link

http://campanian.iodp.org/MoHole/

## Australian Earth Sciences Convention Features Ocean Drilling

In July 2010, a selection of national and international speakers, industry leaders, key decision makers, and assorted geoscientists (650 in all) met in Canberra for the Australian Earth Sciences Convention. Australia and New Zealand (ANZIC) took this opportunity to showcase our past, current, and future IODP expeditions. The following papers, nearly all on preliminary expedition results, were given at an IODP symposium held on 7 July:

- **Kevin Welsh** (keynote speaker) – IODP 318 Cenozoic East Antarctic ice sheet evolution from Wilkes Land Margin sediments: preliminary results.
- **Neville Exon** – Australia's involvement in IODP: what it means for our scientists?
- **Bob Carter** – Preliminary results from IODP Expedition 317 (Canterbury Basin, New Zealand).
- **John Moreau** – Biogeochemical and geomicrobiological evidence for an ultra-deep anaerobic methane oxidation zone in the Nankai Trough subseafloor.
- **Kelsie Dadd** – IODP Expedition 323 in the Bering Sea: environmental change over 5 million years recorded in deep-sea sediment.
- **Christian Ohneiser** – Magnetostratigraphic records from Eocene-Miocene sediments cored in the equatorial Pacific: initial results from the Pacific Equatorial Age Transect (PEAT), IODP Expeditions 320/321.
- **David Murphy** – Sr, Nd, and Pb isotope data from the Shirshov Massif of the Shatsky Rise, northwest Pacific.
- **Simon George** – Geochemistry from the Cante

Many scientists (average of 40–50) attended these talks, which were followed by a number of visits to the IODP exhibition booth. There they asked a range of questions regarding applications for shipboard positions, the science, the life on board ship, and general information about the membership and organization of IODP. ANZIC brochures, *Scientific Drilling* journal, and expedition fact sheets were displayed and distributed. Video presentations, especially those on the Wilkes Land expedition, generated interest.

Please note that there will be an IODP symposium at the 34th International Geological Congress in Brisbane, which is scheduled for 2–10 August 2012. The emphasis is likely to be on the Southern Hemisphere Oceans.

## New Drilling Platform Expands Climate Studies in Lakes

DOSECC's Deep Lake Drilling System (DLDS) platform made its maiden voyage on Lake Van, Turkey in July 2010. The DLDS platform is designed specifically for deep lake drilling and will enable researchers to sample previously inaccessible deep lake sediments. The DLDS platform consists of two main parts: the drilling rig and associated equipment, and the barge itself. The drilling rig is an Atlas Copco T3WDH rig, a top-head-drive rotary rig designed for water well and oil and gas drilling. DOSECC has made extensive modifications to the rig to turn it into a deep coring rig. The DLDS is designed to drill to 1400 m.

The drilling barge, made by Damen in the Netherlands, is a modular system which enables easy shipping anywhere in the world. It is constructed with six separate containers connected in a two-by-three configuration with a moon pool built into one of the modules. The barge is 24.4 m long by 7.3 m wide. Along with the drilling rig, pipe, mud tanks, and associated supplies, the platform also accommodates a science lab and a driller's shack. The science lab is used for on-board sampling from the core catcher and for labeling and orienting the core samples. During the drilling crew shift change, the cores are transported to shore for additional sampling and testing. Four separate winches and anchors with 2 km of cable each keep the barge on station.

In early August, DOSECC operated the barge in Lake Van at a water depth of 360 m. The deepest hole planned for the Lake Van project is 250 m below the lake floor. Upcoming projects for the DLDS include the Dead Sea in Israel and Lake Ohrid in Macedonia. The system will then return to the U.S. following the Lake Ohrid project.

## IODP/ECORD - Canada 2010 Summer School: A Great Success

The summer school by ECORD/IODP-Canada was a great success from 27 June to 12 July. Nineteen students and postdoctoral fellows from Canada, France, Germany, Serbia, Portugal, the U.K, and the U.S.A. participated in a two-week intensive training in marine geology and paleoceanography. Participants had sailing and sampling experience on board the R/V *Coriolis II* in the St. Lawrence Estuary and Saguenay Fjord; on board they acquired theoretical and practical knowledge on cutting-edge techniques for sampling and analyzing geological and geophysical data. Courses, lectures, practical exercises, and laboratory visits were offered at Université du Québec à Rimouski (UQAR), the Institut national de la recherche scientifique - Centre – Eau Terre

The participants during a field trip at the Parc national du Bic. Photo by H. Gaonac'h

Environnement (INRS-ETE), and the Université du Québec à Montréal (UQAM), in addition to field trips in Gaspesia and St. Lawrence Lowlands giving students an extensive scientific portrait of paleoceanography and paleoclimatology in polar and sub-polar environments. This summer school was possible thanks to an impressive group of scientists sharing their knowledge with participants. More than a dozen researchers from ECORD countries actively involved in IODP activities presented the most recent state-of-the-art theories and practices in high latitude geophysics, geochemistry, paleontology, geomorphology, oceanography, sedimentology, sea-ice modeling, and gas hydrates. Speakers included: Hans Asnong, Anne de Vernal, Claude Hillaire-Marcel, and Taoufik Radi (UQAM, Canada), Gilles Bellefleur (GSC-Ottawa, Canada), Xavier Crosta, and Frédérique Eynaud (Université Bordeaux I, France), Mathieu Duchesne (GSC-Québec, Canada), Pierre Francus (INRS-ETE, Canada), Martin Frank (IFM-GEOMAR, Germany), Yves Gélinas (Concordia University, Canada), Joël Guiot and Guillaume Massé (CNRS, France), Patrick Lajeunesse (Université Laval, Canada), Jean-François Lemieux (New York University, U.S.A.), Matt O'Regan (Cardiff University, U.K.), Joseph Ortiz (Kent State University, U.S.A.), Frank Rack (University of Nebraska-Lincoln, U.S.A.), André Rochon, Guillaume St-Onge, and Bjorn Sundby (UQAR, Canada), Ruediger Stein (AWI, Germany).

IODP-Canada is grateful to the many institutions which sponsored this summer school: the GEOTOP Research Center, the Institut des sciences de la mer de Rimouski (ISMER), INRS-ETE, UQAM, the Canadian Consortium for Ocean Drilling (CCOD), the European Consortium for Ocean Research Drilling (ECORD), and the MobilUQ program of the Université du Québec. For more details on the 2010 IODP/ECORD-Canada Summer School, please contact the IODP-Canada office, e-mail: coordinator@mail.iodpcanada.ca.

## IODP/ICDP Canada Booth at GeoCanada 2010

IODP-Canada and ICDP-Canada organized a booth at the most recent Geocanada 2010 meeting in Calgary, Alberta. Many visitors came to the booth open on 10–12 May 2010. GeoCanada 2010 was sponsored by several Canadian associations, notably the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC). The information provided at the booth included the list of recent and current drilling expeditions coordinated by IODP in oceanic environments and by ICDP on continents; it also included the various targeted scientific issues such as past climate change, the geology and geophysics of oceanic and continental crusts, the bottom of the ocean biosphere, available resources such as gas hydrates, triggers in active seismic zones, etc. IODP summer schools organized for summer 2010 were also announced. Students and researchers present at the booth came from the University of Alberta in Edmonton, the Université du Québec à Montréal, and the University of Toronto. This successful activity was part of the IODP and ICDP Canada programs to better promote IODP and ICDP activities in Canada. More information on their homepage: http://www.iodpcanada.ca/, for questions contact: coordinator@mail.iodpcanada.ca.

## Solution for Riser Drilling in Strong Current

In the NantroSEIZE drilling area, the very strong "Kuroshio Current" exists. When a riser is deployed in such a current, Vortex Induced Vibration (VIV) of the riser occurs. VIV is a cross-flow vibration of a circular cylinder placed in a current. Long term VIV will cause fatigue fractures of the riser.

In order to suppress VIV of the riser, JAMSTEC decided to apply a riser fairing device, which is one possible way to suppress VIV. The shape of the fairing is like a fin, and a current against the riser is redirected so that vortex shedding behind the riser is reduced. The fairing also rotates freely about the riser and aligns with direction of the current passively. In this way, VIV is suppressed.

In IODP Expedition 319, the D/V *Chikyu*'s first riser drilling in NantroSEIZE was carried out. Attached to upper riser joints were 132 sets of fairings. Though the duration of strong currents over 2.5 knots was only about 20 hours in this operation, it was confirmed that VIV of the riser was suppressed sufficiently.

In future NantroSEIZE operations, the riser will be exposed to stronger currents for longer periods. The fairing will be essential for the suppression of VIV and the success of NantroSEIZE.

# Schedules

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

| | ESO Operations | Platform | Dates | Port of Origin |
|---|---|---|---|---|
| | Any expedition is not currently scheduled. | | | |
| | **USIO Operations *** | **Platform** | **Dates** | **Port of Origin** |
| 1 | 329 - South Pacific Gyre Microbiology | *JOIDES Resolution* | 09 Oct.–13 Dec. 2010 | Papeete, Tahiti |
| 2 | 330 - Louisville Seamount Trail | *JOIDES Resolution* | 13 Dec. 2010–12 Feb. 2011 | Auckland, New Zealand |
| 3 | 334 - Costa Rica Seismogenesis Project (CRISP) | *JOIDES Resolution* | 16 Mar.–17 Apr. 2011 | Balboa, Panama |
| 4 | 335 - Superfast Spreading Rate Crust 4 | *JOIDES Resolution* | 17 Apr.–20 May 2011 | Puntarenas, Costa Rica |
| 5 | 336 - Mid-Atlantic Ridge Microbiology | *JOIDES Resolution* | mid-Sep.–mid-Nov. 2011 | Bridgetown, Barbados |
| | **CDEX Operations **** | **Platform** | **Dates** | **Port of Origin** |
| 6 | 331 - DEEP HOT BIOSPHERE | *Chikyu* | 01 Sep.–03 Oct. 2010 | Shimizu, Japan |
| 7 | 332 - NanTroSEIZE Stage 2: Riserless Observatory 2 | *Chikyu* | 25 Oct.–12 Dec. 2010 | Shingu, Japan |
| 8 | 333 - NanTroSEIZE Stage 2: Inputs Coring 2 and Heat Flow | *Chikyu* | 13 Dec.–10 Jan. 2011 | Shingu, Japan*** |

* Sailing dates may change slightly. Staffing updates for all expeditions to be issued soon.
** CDEX schedule subject to OTF and SAS approval.
***On-board shift change will take place between Exp. 332 to 333

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

| | ICDP Projects | Drilling Dates | Location |
|---|---|---|---|
| 1 | Snake River Plain | Aug. 2010–Sep.2011 | Idaho, U.S.A. |
| 2 | Campi Flegrei | Sep. 2010–Sep. 2011 | Naples, Italy |
| 3 | Dead Sea | Nov.–Dec. 2010 | Israel, Jordan |
| 4 | Lake Ohrid | May–Jun. 2011 | Macedonia, Albania |
| 5 | COREF | Jun.–Jul. 2011 | Ryukyu Islands, Japan |
| 6 | Songliao Basin | Jun. 2011–Sep. 2012 | Daqing, China |