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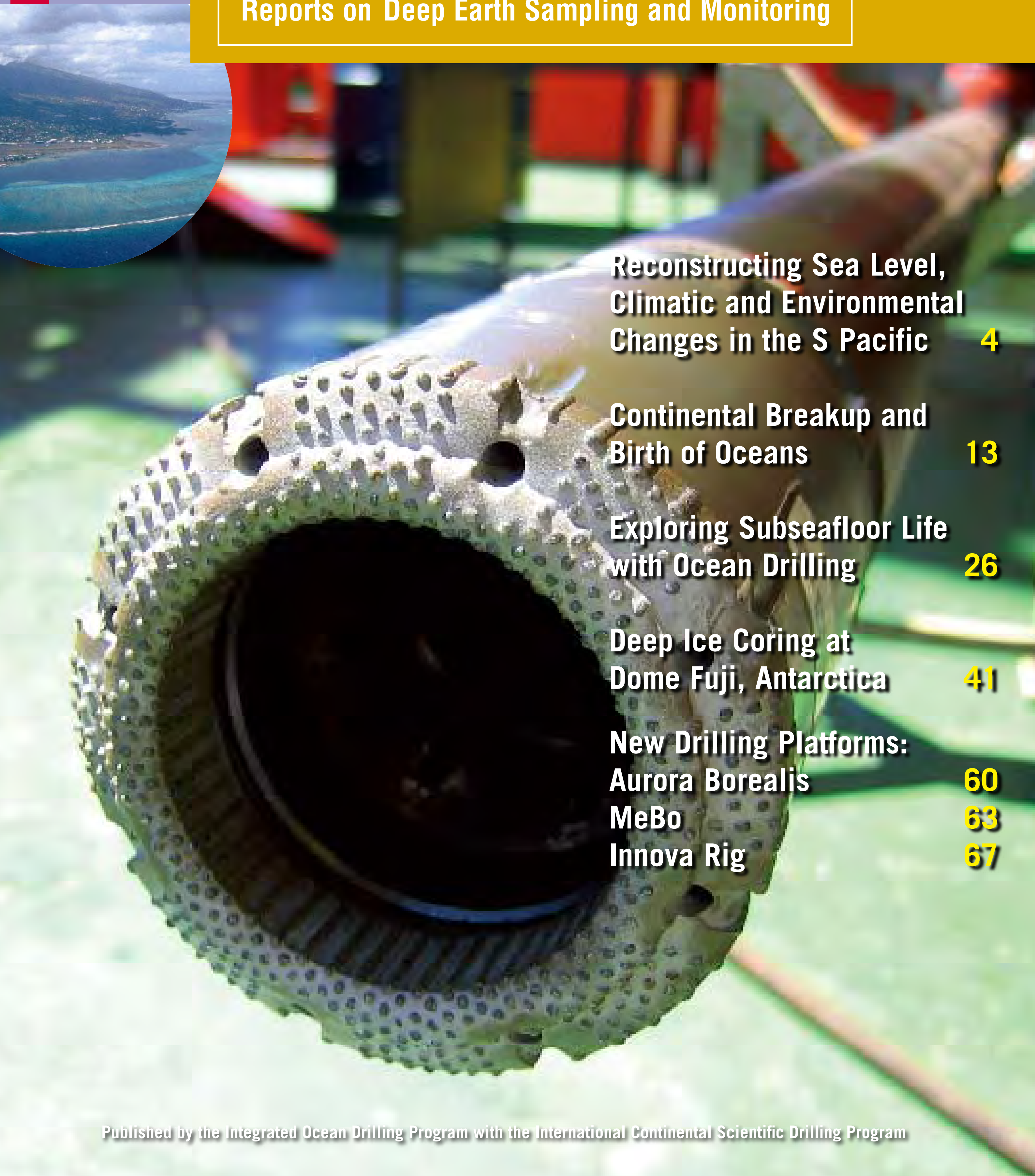
Reports on Deep Earth Sampling and Monitoring



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Editorial Preface

Dear Reader:

Earth sciences are entering an exciting new phase in scientific drilling. Several new projects are starting or expanding, and new drilling tools are being developed. After a 20-month drilling hiatus, IODP now starts its second phase in October 2007 with the first expedition by the new Japanese riser drilling vessel *Chikyu*, and to be followed in early 2008 by expeditions of the totally remodeled riserless drilling vessel *JOIDES Resolution*. ICDP now has access to a completely new portable and state-of-the-art drilling rig, capable of drilling on land to depths of 5 km. And, other innovative projects are rapidly underway such as the MeBo, a containerized drilling device that can be deployed to the seabed from research vessels, and core up to 50 m into the sea floor. Furthermore, the European Commission has rated very highly a proposal to develop an icebreaker with deep-water drilling capability for use in the Arctic. If realized, vastly more ground-breaking data and drill cores can be obtained from the critically under-explored Arctic Ocean. With reference to the international polar year, we also report on the ultra-deep ice coring in Antarctica. This report, together with workshop reports including the research field of the deep biosphere, illustrates that scientific drilling now engages in studies of the lithosphere, the hydro- and cryosphere, the biosphere, and equally importantly, the interactions between Earth's different "spheres".

This exciting development, however, takes place with the background of a troublesome fiscal situation. Dramatic cost increases in all drilling related services, fuel, supplies, and materials impose a heavy fiscal toll on scientific drilling projects. The direct consequence for IODP is that its two permanent drilling vessels cannot be operated throughout the full year on the funds available, but must take up other work during periods of the year. It is hoped that this will generate sufficient program savings to allow IODP to continue operating at the high level one would expect from this world leading program. ICDP is following a similar path, by offering commercial use of the German mobile drilling rig while it is not in use for scientific projects. A new major exploratory challenge for scientific drilling is to see whether this sharing of facilities between science programs and users like industry can develop into mutually rewarding scientific and technological partnerships, or will simply remain a fiscal arrangement of necessity.

The multitude of projects and developments reported here demonstrate a vibrant and ambitious scientific drilling community. The creativity and energy of this growing community bodes well for the future of drilling supported science. So now the scientific drilling community is ready to jointly and boldly go where no man has gone before!

Hans Christian Larsen
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Editor

Front Cover: Drillbit from IODP Expedition 310, Tahiti Sea level. *Photo by Rolf Warthmann (ETH, Zurich).* **Left inset:** Aerial view of the Tahiti barrier reef in the Faaa area. *Photo by Gilbert Camoin.* Read more on page 4.

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

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

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Contents

IODP Expedition 310 Reconstructs Sea Level, Climatic, and Environmental Changes in the South Pacific during the Last Deglaciation

by Gilbert F. Camoin, Yasufumi Iryu, Dave B. McInroy and the IODP Expedition 310 Scientists

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Introduction and Goals

The timing and course of the last deglaciation (19,000–6,000 years BP) are essential components for understanding the dynamics of large ice sheets (Lindstrom and MacAyeal, 1993) and their effects on Earth's isostasy (Nakada and Lambeck, 1989; Lambeck, 1993; Peltier, 1994), as well as the complex relationship between freshwater fluxes to the ocean, thermohaline circulation, and, hence, global climate during the Late Pleistocene and the Holocene. Moreover, the last deglaciation is generally seen as a possible analogue for the environmental changes and increased sea level that Earth may experience because of the greenhouse effect, related thermal expansion of oceans, and the melting of polar ice sheets.

Corals are excellent sea level indicators and can be accurately dated; therefore, studying them helps in the determination of the timing of deglaciation events and the understanding of the mechanisms driving the glacial-interglacial cycles. Coral reefs are also sensitive recorders of past climatic and environmental changes. The skeletal geochemistry of annually-banded massive corals can provide a record of sea surface temperatures (SSTs) and salinities (SSSs). Because the amplitude of the last deglacial sea level rise was at least 120 m (Barbados: Fairbanks, 1989; Bonaparte Basin: Yokoyama et al., 2001; and review in Lambeck et al., 2002), the relevant reef and sediment archives are mostly found on modern fore-reef slopes where they can be investigated by dredging, submersible sampling, and coring. However, the scarcity of such cores and related data hinders our ability to unravel the rate and timing of the last deglacial sea level rise and prevents us from understanding the role of the Pacific Ocean as a climate modulator during the course of postglacial climate change.

Sea level changes and reef development during the last deglaciation: The magnitude and rates of eustatic changes constrain the volumes of ice that accumulated on the continents during the last glacial period, including the Last Glacial Maximum (LGM), and provide direct evidence of the progress of melting of large ice sheets during the last deglaciation.

So far, only three deglaciation curves based on coral reef records have been accurately dated for times reaching the Pleistocene-Holocene boundary—in Barbados between 19,000 and 8,000 yr BP (Fairbanks, 1989; Bard et al., 1990); in Papua New Guinea between 13,000 and 6,000 yr BP (Chappell and Polach, 1991; Edwards et al., 1993), and in Tahiti between 13,850 and 3,000 yr BP (Bard et al., 1996). Of these, the only coral reef record that encompasses the whole last deglaciation is from the Barbados, where it was suggested that this period was characterized by two brief intervals of accelerated melting (meltwater pulses MWP-1A and MWP-1B at ~14,000 and 11,300 yr BP, respectively) superimposed on a smooth and continuous rise of sea level with no reversals (Fairbanks, 1989; Bard et al., 1990). These events would correspond to massive inputs of continental ice to the oceans (i.e., ~50–40 mm y^{-1}, roughly equivalent to an annual discharge of 16,000 km^3 for MWP-1A), and they are thought to have induced reef drowning events (Blanchon and Shaw, 1995). However, the abrupt and significant environmental changes that accompanied the deglacial rise in sea level have barely been investigated, leaving the accurate reconstruction of the event obscured.

The timing, the amplitude, and even the realities of those periods of accelerated sea level rise have been actively debated (Bard et al., 1996; Okuno and Nakada, 1999; Lambeck et al., 2002; Clark et al., 2004). Uncertainties con-

Figure 1. View of Tahiti from the *DP Hunter* during IODP Expedition 310. The picture was taken in the Maraa area in Southern Tahiti while stationed at Site M0007. Photo by Rolf Warthmann.

cerning the general pattern of sea level rise during this time period remain because the apparent sea level record may not be free of tectonic or isostatic complications. The Barbados sea level curve was derived from three separate drowned reefs, and each of these segments is offset from the next. Moreover, these offsets constitute the two rapid meltwater surges; however, because these sites are located close to subduction zones, sea level records derived from them may be impacted by unknown tectonic movements. It is therefore preferable to obtain sea level data from tectonically stable regions truly distant from the former ice sheets ("far-field" sites), sites that are minimally affected by isostatic rebound in relation to changes in ice loading of the lithosphere (Mix et al., 2001; Clark and Mix, 2002).

Tahiti is a volcanic island characterized by slow and regular subsidence rates (~0.25 mm yr^{-1}; Bard et al., 1996) and located at a considerable distance from the major former ice sheets. Therefore, it provides an ideal setting to reconstruct the deglacial rise in sea level and to constrain short-term events that are thought to have punctuated the period between the LGM and the present days.

Climatic variability during the last deglaciation: The tropical Pacific Ocean is known to play an important role in driving and modulating global climate variability and change on a wide range of timescales (Bjerknes, 1969; Pickard and Emery, 1990). Furthermore, climate modeling of global warming implies that the tropical Pacific is pivotal in modulating the timing, regional expression, and magnitude of climate change.

The tropical Pacific may have played an important role in glacial-interglacial timescale climate change, but currently there is debate over exactly what this role was. Additional information is therefore required for a better knowledge on climatic conditions in tropical regions during the last deglaciation, including the changes in the seasonal cycle (amplitude and structure) that are likely to yield important insights into the mechanisms and drivers of climate variability and change.

Scientific objectives of the expedition were:

A) *To establish the course of postglacial sea level rise during the last deglaciation in order to* 1) establish the minimum sea level during the LGM; 2) assess the validity, timing, and amplitude of meltwater pulses and thereby identify the exact sources of the ice responsible for these rapid sea level steps; 3) prove or disprove saw-tooth pattern of sea level rise; and 4) test predictions based on different ice and rheological models.

B) *To define variations in SSTs and SSSs during the last deglaciation* when solar insolation, sea level, and atmospheric CO_2 levels were different from today. The objectives are to 1) reconstruct interannual-decadal climate variability and seasonality (amplitude and structure) in the South Pacific; 2) reconstruct variability and change in interannual including

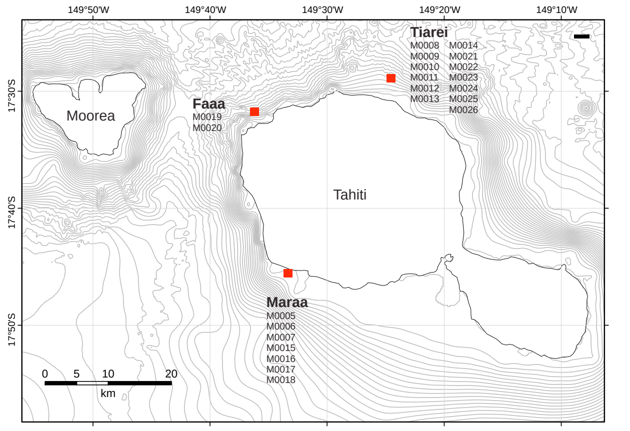

Figure 2. Location of Expedition 310 operations areas around Tahiti.

El Nino Southern Oscillation (ENSO) and decadal-interdecadal including Pacific Decadal Oscillation (PDO)/ Interdecadal Pacific Oscillation (IPO) variability; 3) compare the global variation and relative timing of postglacial warming between the tropical Pacific and the mid- and high-, northern and southern latitudes; and 4) determine major changes in tropical sea surface salinity.

C) *To analyze the impact of sea level and environmental changes on reef development during the last deglaciation*, with a special emphasis on the comprehensive reconstruction of environmental changes (e.g., nutrient concentrations, variations in pH and alkalinity, paleoproductivity, terrigenous and freshwater fluxes), the evolution of the geometry, biological composition, and growth mode of reef frameworks.

D) *To investigate the geomicrobiology processes* on the Tahiti fore-reef slopes to study potential modern counterparts of the microbialites that characterize the last deglacial reef sequence drilled in Papeete (Camoin and Montaggioni, 1994; Camoin et al., 1999). The objectives are to 1) identify the microbial communities that are involved in their formation and 2) to have a better understanding of the environmental significance of those microbial fabrics.

Drilling Sites and Operational Strategy

At Tahiti, recovery of the last deglacial reef sequence required drilling successive reef terraces of various lateral extent that occur at various depths (100, 90, 60, and 40–50 m) seaward of the living barrier reef (Camoin et al., 2003). Preliminary sedimentological and chronological results on the dredged samples have confirmed the significance of these features as unique archives of abrupt global sea level rise and climate change (Camoin et al., 2006). Based on the results of previous drillings on the Papeete reef (Bard et al., 1996; Montaggioni et al., 1997; Camoin et al., 1999 ; Cabioch et al., 1999a) and of the SISMITA cruise (Camoin et al., 2003), we drilled a transect of holes in three areas around Tahiti—offshore Faaa, Tiarei, and Maraa (Figs. 1 and 2). The final and exact locations of the drill holes was determined during the drilling cruise by mapping the nature and morphology of the seafloor with a through-pipe underwater

Figure 3. Core displaying coralgal frameworks heavily encrusted with microbialites (laminated fabrics overlain by dendritic growth forms).

camera. More than 600 meters of reef cores with an exceptional recovery (>90% of the rocks) and quality (Fig. 3) were recovered from thirty-seven holes at twenty-two sites (M0005–M0026) ranging from 41.6 m to 117.5 m water depth. Cores were recovered from 41.6 m to 161.8 m below sea level (mbsl). The recovery was therefore much higher than that obtained during previous Ocean Drilling Program Legs 143 and 144 (Sager et al., 1993; Premoli Silva et al., 1993) related to shallow-water carbonates.

Cored material shows that the fossil reef systems around Tahiti are composed of two major lithological units: a last deglacial sequence (Unit I) and an older Pleistocene sequence (Unit II). Those two major units have been divided into subunits based on coral assemblages and internal structure.

The set of deployed borehole geophysical instruments was constrained by the scientific objectives and the geological setting of the expedition. A suite of downhole geophysical methods was chosen to obtain high resolution images of the borehole wall (OBI40 and ABI40 televiewer tools; Fig. 4), to characterize the fluid nature in the borehole (IDRONAUT tool), to measure borehole size (CAL tool), and to measure or derive petrophysical and geochemical properties of the reef units such as porosity, electrical resistivity (DIL 45 tool), acoustic velocities (SONIC tool), and natural gamma radioactivity (ASGR tool). A total of ten boreholes were prepared for downhole geophysical measurements, which were performed under open borehole conditions (no casing) with the exception of a few spectral gamma ray logs. Nearly complete downhole coverage of the postglacial reef sequence has been obtained from 72 mbsl to 122 mbsl and from 41.65 mbsl to 102 mbsl at the Tiarei sites and the Maraa sites, respectively. Partial downhole coverage of the underlying older Pleistocene carbonate sequence has been acquired at both sites.

Samples from Tahiti drill cores were analyzed for evidence of microbial activity, possibly related to the formation of microbialites. Onboard measurements have shown a certain degree of microbial activity directly attached to rock surfaces; cultivation and microscopic observations were also carried out onboard. According to the adenosine triphosphate (ATP) activity measurements along the drill cores, the uppermost part (0–4 mbsf of the Tahiti reef slopes) is the most active zone. Pure microbiological activity was only observed in reef cavities where prokaryotic biofilms have appropriate conditions to develop. Northwestern Faaa Hole M0020A and southwestern Maraa Holes M0005C, M0007B, M0007C, M0015B, and M0018A were more active than the northeastern Tiarei sites where usually no living biofilm could be detected in cavities along the cores.

Last Deglacial Sequence

Composition: The last deglacial sequence is mostly composed of coralgal frameworks heavily encrusted with microbialites (Fig. 3), locally associated or interlayered with skeletal limestone and/or loose skeletal sediments (rubble, sand, and silt) rich in fragments of corals, coralline and green (*Halimeda*) algae, and, to a lesser extent, bryozoans, echinoids, mollusks, and foraminifers (mostly *Amphistegina* and *Heterostegina*). The amounts of volcaniclastic sediments (e.g., silt- to cobble-sized lithic volcanic clasts, mineral fragments, clays) are highly variable, from mere sand and silt impurities in the carbonate rock units to minor components (<50 vol-%) in carbonate sand units to major components (>50 vol-%) in sand/silt (or sandstone/siltstone) interbedded with carbonate beds. The last deglacial sequence at Tiarei has a greater volcaniclastic component than the ones at Maraa and Faaa; this difference is observed on digital image scans and quantified by diffuse color reflectance spectrophotometry and magnetic susceptibility core logs.

Corals are well preserved, forming seven distinctive coral assemblages characterized by various morphologies (branching, robust branching, massive, tabular, foliaceous, and encrusting) that determine distinctive framework internal structure. Several coral assemblages are intergradational vertically and laterally. Robust branching (e.g., *Pocillopora* and *Acropora*) and, to a lesser extent, tabular (e.g., *Acropora*) corals are usually thickly encrusted with nongeniculate coralline algae and microbialites to form dense and compact frameworks; vermetid gastropods and serpulids are locally associated with coralline algae. Foliaceous and encrusting coral colonies (e.g., *Montipora*, *Porites*, *Pavona*, *Leptastrea*, *Psammocora*, *Astreopora*, agariciids and faviids) are thinly coated with coralline algae and microbialites to form loose frameworks. Large primary cavities in coralgal frameworks are open or partially filled with skeletal sands and gravels locally mixed with volcanic elements. The open framework and centimeter- to decimeter-sized pores result in a highly variable system in which physical properties change on a centimeter scale and may range from low porosity, high density, and velocity to 100% open pore space.

Abundant microbialites represent the major structural and volumetric component of the last deglacial reef sequence (Figs. 3 and 4). The presence of microbialites at all depths in the sequence indicates that they formed in various parts of the reef tracts (Camoin et al., 2007). They developed within the primary cavities of the reef framework, where they generally overlie coralline algal crusts to form dark gray massive crusts as thick as 20 cm; they also develop in bioerosion cavities. Microbialites correspond to a late stage of encrustation of the dead parts of coral colonies, or more commonly, of related encrusting organisms (coralline algae and crustose foraminifers), implying that some time elapsed prior to the formation of the microbialites and that there was generally no direct inter-community competition for space between coralgal and microbial communities. This is also reflected by the age differences between corals, encrusting organisms, and overlying microbialite crusts (Camoin et al., 2007). Microbialites generally comprise a suite of fabrics, including two end-members represented by laminated fabrics and thrombolitic to dendritic accretions; thrombolites usually represent the last stage of encrustation. The thickness and morphology of the microbial crusts are closely related to the morphology and size of the cavities in which they are developed. In bindstone formed by encrusting coral assemblages, microbialites are dominated by thrombolitic fabrics, whereas in frameworks made of branching and massive coral colonies, they are characterized by the development of compound crusts, up to 15 cm thick, formed by a succession of laminated and thrombolitic fabrics. Preliminary results obtained on lipid biomarkers imply that carbonate precipitation processes were related to the activity of heterotrophic bacteria and were in agreement with the stable isotope data (Heindel et al., 2007).

At all sites, the top of the last deglacial carbonate sequence is characterized by the widespread development of thin coralline algal crusts indicating deep water environments. Extensive bioerosion, dark yellow-reddish to brown staining (manganese and iron) of the rock surface, and hardgrounds are common within the top 2–3 m of the sequence.

<u>*Distribution of the last deglacial reef sequence*</u>: At all sites, the last deglacial sequence displays similar trends, although it displays specific characters in each area.

The Tiarei area is characterized by the occurrence of two successive ridges seaward of the living barrier reef (Camoin et al., 2003; Camoin et al., 2006). The outer ridge coincides with a marked break in slope, and its top is located at 90–100 mbsl, whereas the inner ridge is located on an extensive terrace, and its top occurs at 60 mbsl. On the outer ridge, the last deglacial sequence was recovered from 81.7 mbsl to 122.12 mbsl at sites 9, 21, 24, 25 and 26; the thickest continuous sequence, 29.98 m, was recovered from Holes M0021A and M0021B (Fig. 6). On the inner ridge, the last deglacial sequence (recovered from 68 mbsl to 92–98 mbsl at site 23) is 24–30 m thick. On both sides of the outer ridge (Holes M0010A–M0014A), the last deglacial sequence (recovered from 78.85 mbsl to 117.98 mbsl) includes reef units overlain by volcaniclastic sediments. At Hole M0008A, which is located on the flat area extending between the two ridges, the 38.7-m-thick sequence (64.15–102.85 mbsl) consists only of volcaniclastic sediments.

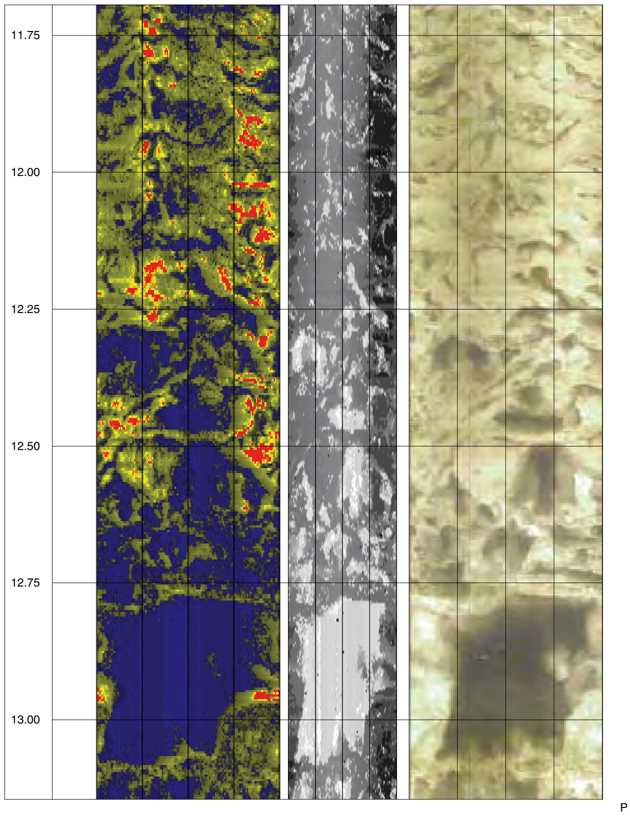

Figure 4. Acoustic (left) and optical (right) images of a coralgal framework heavily encrusted with microbialites. Note the abundance of large cavities in the reef framework.

Two transects were drilled in the Maraa area. The western transect includes Sites M0007, M0005, and M0006 (landward to oceanward) in water depths ranging from 41.65 m to 81.58 m, and the thickness of the last deglacial sequence ranges from 33.22 m to 44.56 m at sites M0005 and M0007, respectively (Fig. 7). Sites M0017, M0015, M0018, and M0016 (landward to oceanward) in water depths ranging from 56.45 m to 81.8 m define the eastern transect; the thickness of the last deglacial sequence ranges from 35.44 m in Hole M0015A at 72.15 mbsl to 39.05 m in Hole M0018A at 81.8 mbsl (Fig. 8).

In the Faaa area, the last deglacial sequence is 62.5 m and 36.5 m thick at Sites M0019 (58.5 mbsl) and M0020 (83.3 mbsl), respectively.

<u>*Sea level issues*</u>: Coralgal assemblages identified in the Tahiti cores can be considered as reliable depth indicators for the reconstruction of sea level changes. Dominant species of coralline algal assemblages include *Hydrolithon onkodes*, *H. reinboldii*, *Lithophyllum insipidum*, *L. pygmaeum*, *Neogoniolithon brassica-florida*, and *Mesophyllum erubescens*;

Figure 5. View of corals from the surface of the Tahiti reefs. Photo by Gilbert Camoin

they provide paleowater depth estimates based on their comparison with modern counterparts. Coral assemblages are dominated by *Porites*, *Pocillopora*, *Acropora*, and *Montipora* genera, which form distinctive assemblages that are indicative of a range of modern reef environments, from the upper to middle reef slope to deep reef slope (0–30 m deep; Sugihara et al., 2006), in agreement with earlier studies on Tahiti (Montaggioni et al., 1997; Camoin et al., 1999; Cabioch et al., 1999a) and other Indo-Pacific reef sites (Camoin et al., 1997, 2004; Montaggioni and Faure, 1997; Cabioch et al., 1999b; Sagawa et al., 2001).

Corals are well preserved, as the great majority of the specimens exhibit less than 1% calcite in their skeleton, indicating that they were not subjected to diagenetic alteration. Preliminary U-series dating results of selected corals indicate that the cored last deglacial sequence covers at least the 16,000–8,000 yrs BP time span, and suggest a non-monotonous sea level rise during that period. Additional data will be necessary to constrain it accurately (Deschamps et al., 2006, 2007). Tahiti is therefore the second region, after Barbados, where coral reef records encompass the MWP-1A and MWP-1B events centered at ~14,000 yr BP and 11,300 yr BP, respectively.

Paleomagnetic and rock magnetic testing are being carried out on all of the studied cores. The natural remanent magnetization (NRM) data obtained on microbialites show that directions have an average magnetic inclination that is very close to that expected at the site latitude from a simple dipole field. Moreover, the stratigraphic variations in inclination can be correlated between local sites, and they may also provide an independent chronostratigraphy for estimating the timing of microbialite growth within the reef primary cavities. Stratigraphic variations in several rock magnetic parameters can also be correlated between local sites, which may provide an independent record of environmental variability within the coral reef over time.

Reef development issues: At each drill site, the cored reef sequences are continuous, implying that there was no major break in reef development during the 16,000–8,000 yrs BP time span, and thus raising the question of the occurrence of reef drowning events as described in the Barbados record (Blanchon and Shaw, 1995). This possibility suggests that environmental conditions in Tahiti were optimal for reef development, and no long-term environmental changes occurred during that period, although changes in coralgal assemblages may reflect variations in environmental parameters (e.g., water depth and energy, light conditions, terrigenous fluxes, nutrient concentrations, etc.). The deeper water facies that form the top of the last deglacial sequence occur gradually shallower towards the modern reefs along the drilled transects, thus indicating a general backstepping of the reef complex as a response to sea level rise during the last deglaciation.

Paleoclimate issues: About thirty meters of the reef cores consist of massive coral colonies, mostly of the genus *Porites*, and concern successive time windows covering most of the 16,000–8,000 yrs BP period. For paleoclimatic objectives, preliminary sub-seasonal records have been already obtained on selected time windows (Felis et al., 2007).

Older Pleistocene Carbonate Sequence

An older Pleistocene carbonate sequence has been recovered below the last deglacial sequence at most sites (Figs. 6, 7, and 8). The contact between the last deglacial sequence and the older Pleistocene sequence is characterized by an irregular unconformity. The change in physical properties at this contact is sharp and abrupt—density, velocity, and magnetic susceptibility increase, and porosity decreases. The depth below present-day sea level of the top of the older Pleistocene sequence is highly variable, ranging from about 90 mbsl on the inner ridge of Tiarei and proximal Maraa sites to 122 mbsl on the outer ridge of Tiarei and distal Maraa sites. This variability indicates a rugged morphology of the Pleistocene carbonate substrate prior to the development of the last deglacial sequence.

Composition of the older Pleistocene carbonate sequence: The older Pleistocene carbonate sequence is mostly comprised of reef deposits and has been detailed in holes M0009D (Tiarei area; 122–147 mbsl; Fig. 6) and M0005D (Maraa area

92–162 mbsl; Fig. 7). Three major distinctive lithological subunits are usually closely associated:

- well lithified skeletal packstone/grainstone to floatstone/rudstone, rich in rhodoliths, and coral and algal fragments,
- well lithified coralgal frameworks exhibiting microbialite fabrics and associated with skeletal packstone/grainstone to floatstone, and
- rubbles and gravels primarily composed of coral clasts, limestone clasts, volcanic pebbles, and reworked coral colonies.

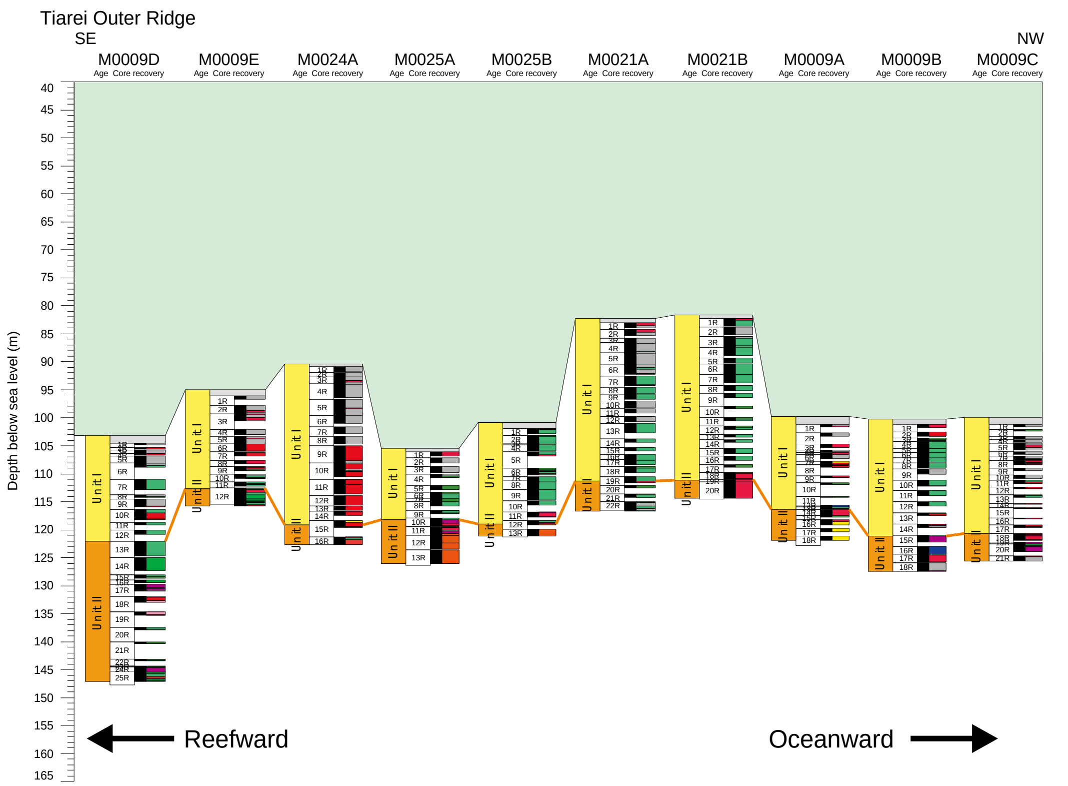

Figure 6. Lithostratigraphic summary of holes on the Tiarei outer ridge. Holes M0009D, M0009E, M0024A, M0025A, M0025B, M0021A, M0021B, M0009A, M0009B, and M0009C.

Ungraded unlithified volcaniclastic silt to sand, including scattered skeletal grains and sandy skeletal grainstone rich in volcanic grains, large coral clasts, and skeletal fragments, are clearly subordinate.

Several sedimentological features indicate that the older Pleistocene carbonate sequence has undergone several phases of diagenetic alteration resulting in tight, low-porosity, high-velocity limestones with much less variation in physical properties than observed for the last deglacial sequence. Several successive unconformities occur in the upper part of the older Pleistocene carbonate sequence and suggest that this sequence is composed of successive chronological units. Those unconformities are associated with several lines of evidence of subaerial diagenetic alteration, including the alteration of coral skeletons and skeletal grains, and the occurrence of abundant solution cavities rimmed with multiple generations of cement crusts and/or displaying several generations of sediment infillings and yellow and brown to red-brown staining. Local multiple bored and encrusted surfaces (hardgrounds) occur at the top of that sequence.

Chronology: The dating potential of the corals occurring in that sequence is generally limited by the amount of diagenesis they have suffered, but the preservation of some specimens was good enough to obtain reliable ages by U-series dating (Thomas et al., 2006).

Paleomagnetic studies provide chronological constraints on reef unit succession by identifying well dated paleointensity lows and geomagnetic excursions. The NRM is mostly carried by a mixture of titano-magnetite grains in the pseudo-single domain range. Based on the occurrence of excursional instabilities in two depth intervals, reef units have been attributed to highstand (isotopic stages 5 and 7) and lowstand reef units (isotopic stages 6 and 8) (Ménabréaz, 2007).

Geomicrobiology of Modern Reef Slopes

Biofilms recovered during the IODP Expedition 310 are diverse in structure and color. Additionally, finely laminated, 1-mm-diameter vertically upward growing columns referred to as endostromatolites were found within some reef cavities (McKenzie et al., 2007). Biofilms appear to have high diversity in macroscale observations, and they are equally diverse and heterogeneous in microscale resolution, as observed by scanning electron microscopy (SEM). In some samples, it was possible to define spherical assemblages of calcium carbonate minerals embedded in microbial exopolymeric substances (EPS).

Some evidence for heterotrophic metabolic activities is shown by exoenzyme measurements, which vary in the different biofilm samples. For instance, samples from holes M0020A (4.51 mbsf) and M0009D (3.64 mbsf) showed high phosphatase activity, suggesting the occurrence of a heterotrophic community that preferentially degrades organic-

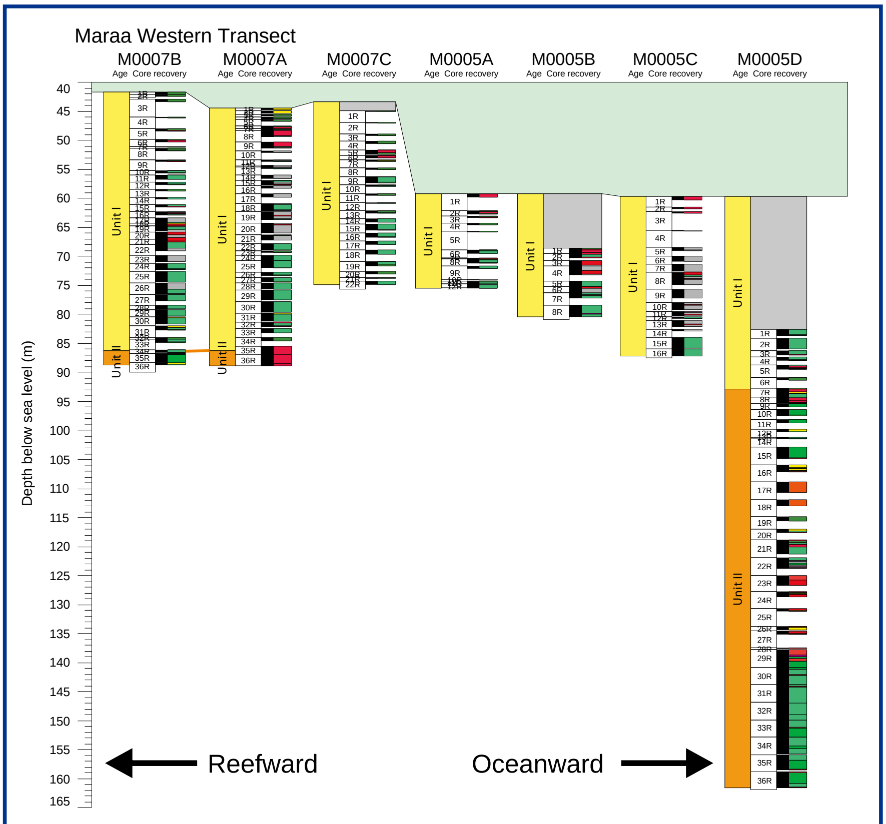

Figure 7. Lithostratigraphic summary of holes on the Maraa western transect (holes M0007B, M0007A, M0007C, M0005A, M0005B, M0005C, and M0005D).

bound phosphate compounds such as phospholipids or nucleic acids. In contrast, hole M0007B (6.28 mbsf) showed only glucosidase and aminopeptidase activity, which indicates degradation and metabolization of polysaccharides and proteins.

Isolation of microorganisms from biofilm samples was performed on agar plates using a medium that is selective for heterotrophic bacteria. After two weeks incubation time, ten different heterotrophic colonies could be isolated. From experiments intended to locate anaerobes, only one isolate was found. Distinct groups of microorganisms are associated in the biofilm that could range from aerobic to anaerobic. The occurrence of pyrite well distributed in the sediment supports the prevalence of a certain degree of anoxia in the environment.

Concluding Remarks and Future Plans

The 600 meters of reef cores with a very high recovery (>90% of the carbonates) were retrieved from thirty-seven holes in 40–120 m water depth and situated on transects in three different areas around Tahiti during the IODP Expedition 310. They provided an exceptional and high resolution record of sea level, climatic, and environmental changes during part of the last deglaciation (about 400 m of cores recovered at 40–122 m below current sea level) and several time windows from the Pleistocene (about 200 m of cores recovered at 85–160 m below sea level).

The preliminary dating results indicate that the cored last deglacial sequence should cover at least the 16,000–8,000 yrs BP time span. Tahiti is therefore the second region, after Barbados, where coral reef records encompass the meltwater pulse events centered at ~14,000 yr BP and 11,300 yr BP (MWP-1A and MWP-1B, respectively). Huge coral colonies, chiefly *Porites* genus, were found in thirty meters of reef cores; these cores cover successive time windows in most of the 16,000–8,000 years period. The study of those colonies will address interannual/decadal-interdecadal climate variability and seasonality (amplitude and structure) in the south Pacific during the last deglaciation, and will present data that might aid modelling of future global warming. In particular, the high recovery combined with the high resolution downhole measurements provides potential for resolving in unprecedented detail the abrupt and significant environmental changes that accompanied the deglacial sea level rise.

The investigation of the 200 meters of cores retrieved from the older Pleistocene carbonate sequences might provide fragmentary information on sea level and reef growth for time windows concerning several isotopic stages.

The geomicrobiological pilot study of living biofilms bearing carbonate precipitates that were sampled *in situ* within cavities underpins a new field of research regarding the development of microbial communities on modern reef slope environments. It will be useful to the nature and environmental significance of microbialite fabrics that form an essential component of the last deglacial reef sequence.

Plans for supplementary drilling operations at four sites offshore the Australian Great Barrier Reef are currently being prepared for possible implementation during 2008–2009.

Acknowledgements

We would like to thank all the people and institutions including the ODP and IODP scientific advisory structure that helped us to pursue this ambitious and challenging project and make it into a very successful expedition with unprecedented recovery of shallow water carbonate rocks.

The ECORD Science Operator (ESO) and its subcontractors made very strong efforts to make this program happen in the best conditions during all stages from planning and

drilling through final core description and sampling at the premises of the IODP Bremen Core Repository.

The talented drillers from Seacore Ltd. did an incredible job by delivering exceptional cores, always with humor and grace. We cannot end without mentioning the crew of the *DP Hunter* and Captain William Roger who made our life very pleasant during the expedition.

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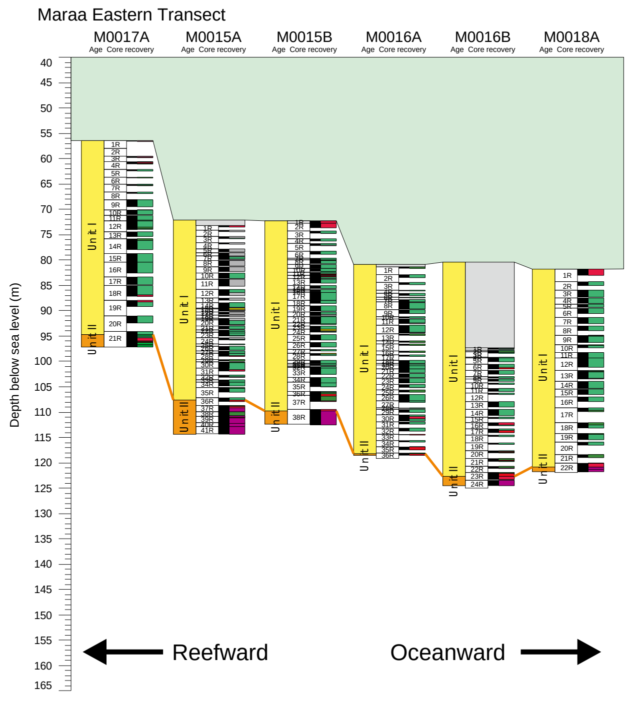

Figure 8. Lithostratigraphic summary of holes on the Maraa eastern transect (Sites M0017, M0015, M0018, and M0016).

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Related Web Links

http://www.eso.ecord.org/expeditions/310/310.htm

http://www.rcom.marum.de/English/Tahiti_Sea-Level_Expedition_2005.html

COBBOOM: The Continental Breakup and Birth of Oceans Mission

by Dale S. Sawyer, Millard F. Coffin, Timothy J. Reston, Joann M. Stock, and John R. Hopper

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Introduction

The rupture of continents and creation of new oceans is a fundamental yet primitively understood aspect of the plate tectonic cycle. Building upon past achievements by ocean drilling and geophysical and geologic studies, we propose "The Continental Breakup and Birth of Oceans Mission (COBBOOM)" as the next major phase of discovery, for which sampling by drilling will be essential.

In September 2006, fifty-one scientists from six continents gathered in Pontresina, Switzerland to discuss current knowledge of continental breakup and sedimentary basin formation and how the Integrated Ocean Drilling Program (IODP) can deepen that knowledge (Coffin et al., 2006). Workshop participants discussed a global array of rifted margins (Fig. 1), formulated the critical problems to be addressed by future drilling and related investigations, and identified key rift systems poised for IODP investigations.

Past Achievements

Scientific ocean drilling has played an essential role in the exploration of rifted continental margins. The North Atlantic Rifted Margins (NARM) endeavor of the Ocean Drilling Program (ODP) addressed conjugate margin pair rift systems ranging from "magma-dominated" (Norway/British Isles-Greenland margins of the offshore-onshore early Tertiary North Atlantic large igneous province (LIP)) to "magma-starved" (Iberia-Newfoundland margins of Late Triassic to Early Jurassic age, Fig. 2.) Geophysical studies and drilling results from these two conjugate pair rift systems have profoundly changed our view of the processes responsible for such margins.

The drilling of 'seaward dipping reflector' (SDR) wedges of the North Atlantic LIP off the British Isles (Roberts et al., 1984), Norway (Eldholm et al., 1987, 1989) and SE Greenland (Duncan et al., 1996; Larsen et al., 1994, 1999) confirmed them to be a thick series of subaerial lava flows covering large areas. Lavas on the landward side of the SDRs show geochemical evidence of contamination by continental crust, implying that they rose through continental crust during early rifting, whereas oceanward SDR lavas appear to have formed at a seafloor spreading center resembling Iceland. Drilling results from these margins document extreme magmatic productivity over a distance of at least 2000 km during continental rifting and breakup with temporal and spatial influence of the Iceland plume during rifting, breakup, and early seafloor spreading (Saunders et al., 1998).

Other margins such as Iberia-Newfoundland (Tucholke et al., 2007) appear magma-starved and have been hyperextended by progressive rifting (Lavier and Manatschal, 2006) in stages, with distinct tectonic characteristics controlled by the rheological effects of the gradual thinning of continental crust and uplift of the underlying mantle (Fig. 3). When the crust has been thinned by normal faulting to less than ~10 km, it becomes entirely brittle (Pérez-Gussinyé and Reston, 2001), and tectonism then transitions to spatially focused, closely spaced normal faults that sole into a serpentine detachment at the crust mantle boundary that eventually unroofs upper mantle rocks along a detachment fault exposed at the seafloor. Exhumation of upper mantle rocks continues over a potentially wide region, until mantle uplift generates sufficient magma to initiate seafloor spreading (Tucholke et al., 2007). These results suggest that depth-dependent stretching (DDS) and detachment faulting are major controls on continental rupture and ocean formation.

The ODP also addressed active rifting along a low-angle normal fault in the Woodlark Basin that is propagating into continental lithosphere (Huchon et al., 2002; Taylor et al., 1999a, b).

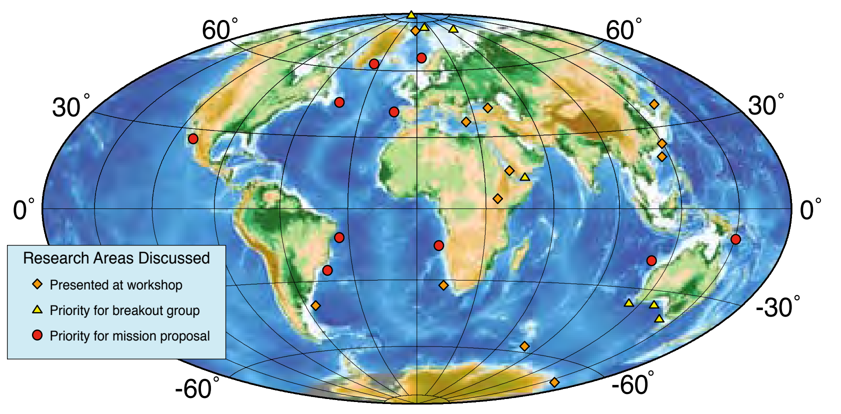

Figure 1. Global overview of continental rifts and rifted margins discussed at the workshop. Red dots highlight initial priority areas for COBBOOM.

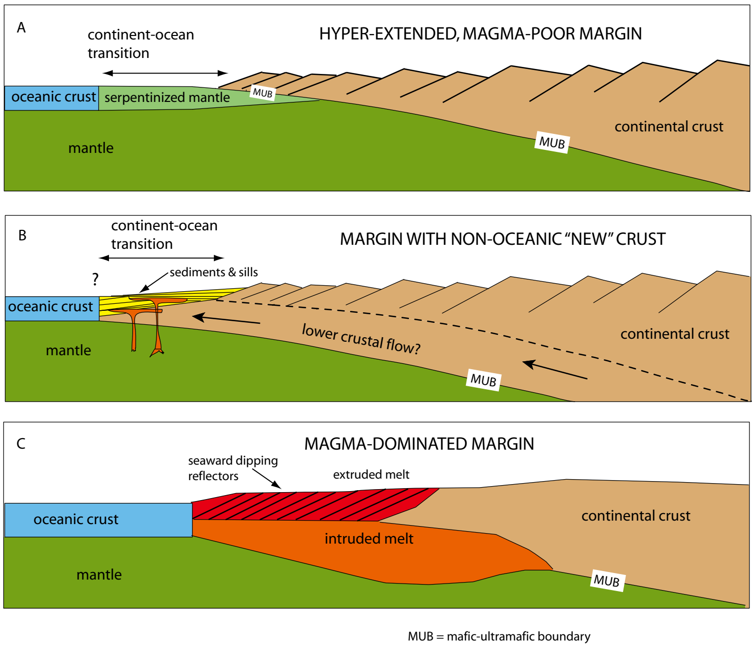

Figure 2. Schematic cross sections of [A] hyper-extended (e.g., Iberia-Newfoundland), [B] non-oceanic 'new' crust (e.g., northern Gulf of California), and [C] magma-dominated (e.g., NW Europe-E Greenland, NW Australia) divergent continental margins.

Scientific Objectives Associated with Continental Rifting

Variations in the importance and, in particular, the volume of magmatism have led to the classification of margins as "volcanic" or "non-volcanic" (Mutter et al., 1988); however, this binary dichotomy fails to adequately reflect that rifted margins form a spectrum from magma-rich to magma-poor. The key distinction is whether magmatism is more or less than expected from the degree of lithospheric thinning and passive asthenospheric upwelling of normal temperature mantle. Equally important are the timing of magmatism and the strain distribution across margins, i.e., hyper-extended versus a more abrupt transition between continental and oceanic lithosphere. Because a continuum between possible end-members may exist, the focus should be on understanding the fundamental processes causing such variations. Key aspects of continental breakup can only be addressed by drilling and associated studies (Table 1).

More specifically, we need to determine the following at multiple, carefully selected rifted margins: 1) uplift and subsidence history; 2) ages and facies of synrift and syn-faulting sediment; 3) timing, volume, chemistry, and style of magmatism; 4) orientation of deformation fabrics, including faults; and 5) ages and facies of postrift sediment. Such information can be used to infer distribution of strain in space and time; deformation mechanics and dynamics; processes within the mantle, including depth and degree of melting, melt migration, and infiltration; and mantle composition, heterogeneity, and dynamics.

We propose drilling programs on well characterized and representative examples, conjugate where possible, of both active and mature rifted margins ranging from magmatic to amagmatic and abrupt to hyperextended. The rift systems described below constitute an initial focus of investigations for COBBOOM.

Gulf of California

Key Aspects and Problems to be Addressed: The active Gulf of California rift system (Fig. 4) varies along strike in crustal thickness, synrift sediment facies, amount of magmatism, structural style, and width of new seafloor (Lizarralde et al., 2007). The northern basins host an enigmatic type of crust that is 15–20 km thick, characterized by gravity anomalies and seismic velocities suggestive of silicic as opposed to basaltic material (González-Fernández et al., 2005). Low-angle normal faults are also accessible to both onshore sampling and drilling. In the central basins, magma-sediment interactions and fluid/geochemical fluxes, including methanogenesis, will be studied (Fig. 5). In southern segments, the processes and timing of the synrift to postrift transition (breakup unconformity, basin evolution, margin uplift or subsidence) will be examined.

Regional Setting and Background: The system formed from a major reorganization of the Farallon-North American plate boundary during Neogene time (Lonsdale, 1989). Narrow perched basins adjacent to seafloor spreading centers characterize the southernmost segment, whereas diffuse deformation in an apparent continental setting dominates the northern Gulf (Persaud et al., 2003). In the central Gulf, two segments of the Guaymas basin are narrow and

Table 1. Key aspects of continental breakup.

Rift initiation	Driving forces, rift localization, lithospheric strength, thermal structure.
Tectonics of rifting	Distribution of strain, rheological evolution, mechanisms of crustal thinning, strength of faults, 3-D rift geometry, mantle exhumation, transition to seafloor spreading.
Magmatism during rifting	Melt-rift interactions, mantle heterogeneities, melt production into seafloor spreading stage, controls on melt production.
Initiation of seafloor spreading	When and where, development of seafloor spreading magnetic anomalies, mantle thermal structure, mantle sources.
Sedimentary processes and basin evolution	Stratigraphic responses to rifting and breakup, stratigraphy-strain rate relationships, fault patterns and evolution, interactions among erosion, sedimentation, and tectonism.
Environmental consequences & impact	Magma interactions with sediment, hydrosphere, and the atmosphere; tectonic and magmatic controls on ocean gateways.

have slightly thicker crust, suggesting more magmatic input, whereas four segments of the south-central domain are wide, magma-poor rifts (Lizarralde et al., 2007). Simple plate kinematics cannot explain these changes in style because of constant total strain along the rift axis. Rather, along strike variation in pre-existing lithospheric and mantle structure, thermal state, and sediment inputs must have controlled this development.

Proposed Drill Sites: Several thousand kilometers of multichannel seismic lines (Persaud et al., 2003; Lizarralde et al., 2007; González-Fernández et al., 2005; Aragón-Arreola and Martín-Barajas, 2007) image key structures of the rift basins well suited for addressing the following topics: 1) the possible role of lower crustal flow to fill the gap created by rifting; 2) the role of detachment faults in early rifting and/or in delaminating continental crust; 3) differences in magmatism in adjacent rift segments along strike; and 4) the relationships between magmatism and global environmental changes (Svensen et al., 2004; Dickens, 2004).

In the northern Gulf (Fig. 4) high heat flow and thick sediment may have caused lower crustal flow and a diffuse rift with enigmatic transitional crust (González-Fernández et al., 2005). It is feasible that sites can sample possible low-angle normal faults and a complete sedimentary section constraining the age of rifting. Igneous intru-

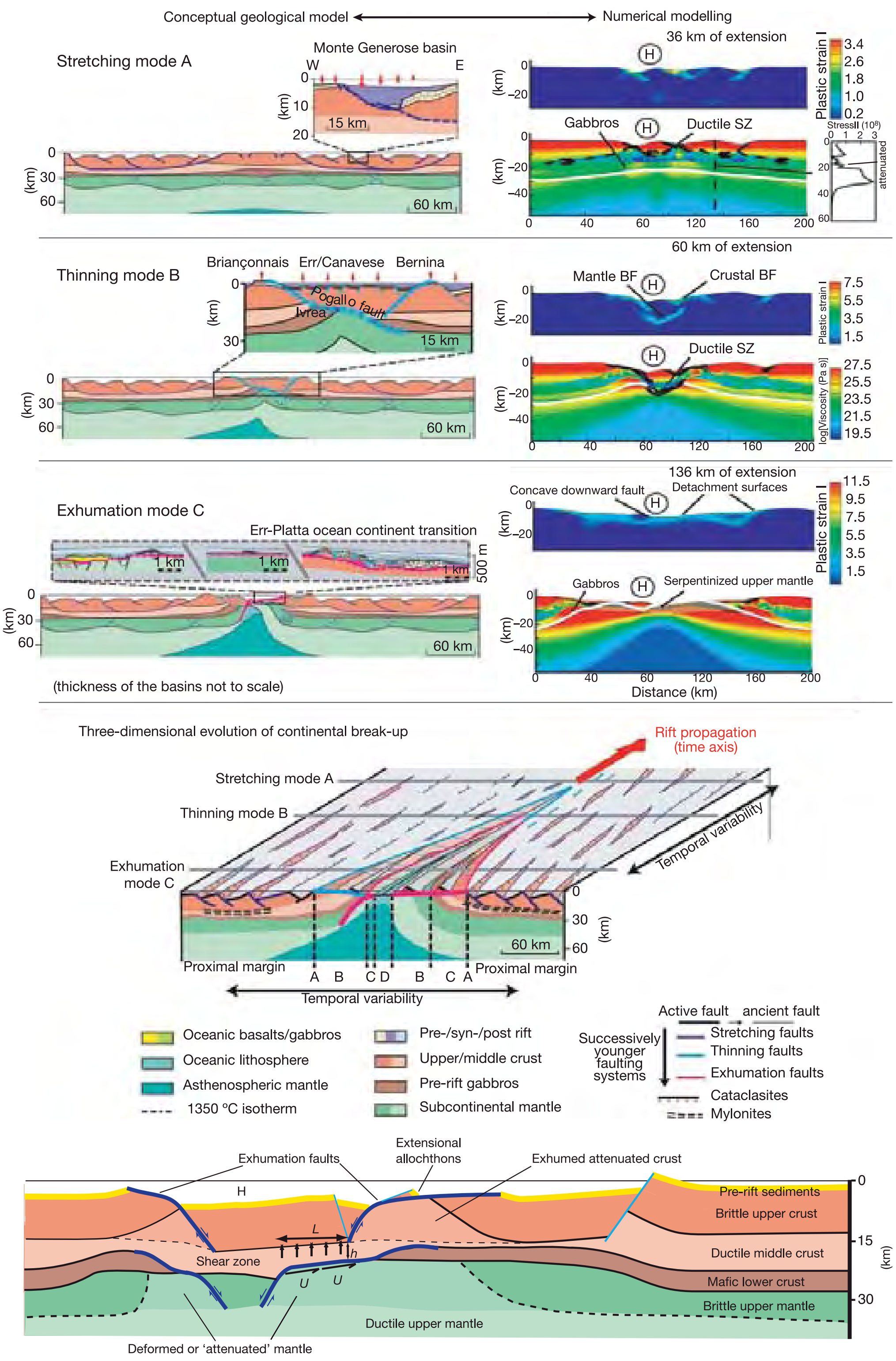

Figure 3. Modeling of the evolution of a continental rift in space and time, not including decompression melting, to better understand the hyper-extended margins of Newfoundland and Iberia (Lavier and Manatschal, 2006). (upper and middle) Conceptual geological and numerical models for different phases of extension that are distinguished by different styles of deformation. The stretching mode [A] is characterized by listric faulting and differential subsidence of half-grabens. The thinning mode [B] is the least documented of the modes, but it can be characterized by maximum thinning of the lithosphere and the presence of a major ductile shear zone accommodating differential motion (up to 10 km upward) between the upper crust and the lower crust/upper mantle. It is accompanied by relatively little uplift of the rift flanks and subsidence in the hanging wall. The exhumation mode [C] is well documented and distinguished by the exhumation of serpentinized upper mantle from <10 km depth along a downward-concave fault. Note the similarity between the observed and modeled structures. (lower) Conceptual model for the thinning phase during continental breakup. Note that thinning is accommodated by the simultaneous exhumation of middle crust and upper mantle.

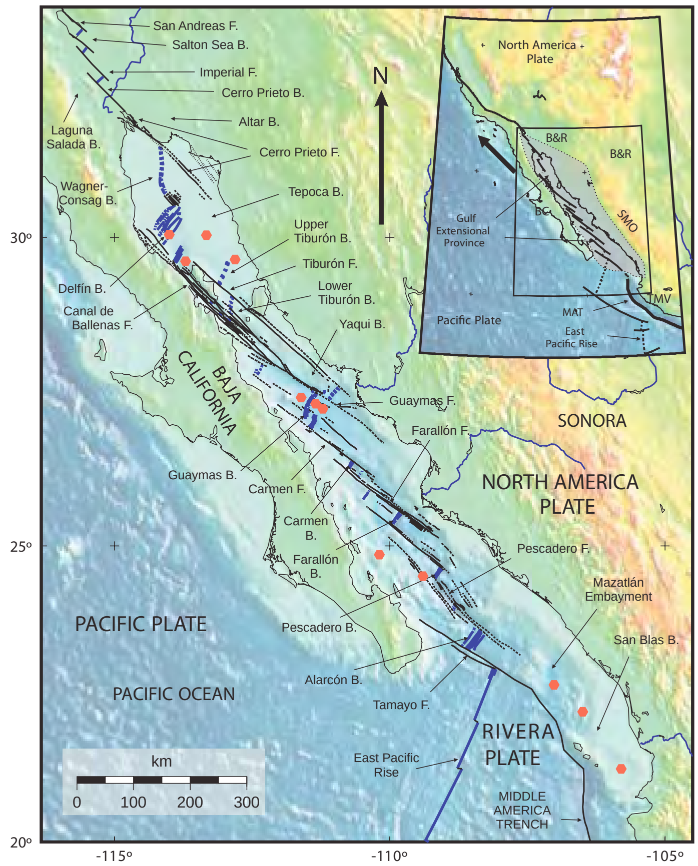

Figure 4. Tectonic map with digital elevations of the Gulf of California region, modified from Aragón-Arreola (2006). This region hosts the modern transtensional boundary between the Pacific and North America plates, comprising spreading centers or extensional basins (blue lines) and faults (black lines). Modern and abandoned basins of the plate boundary are labeled. Red dots show proposed IODP sites. Abbreviations: F=fault, B=basin. Inset: regional map of plate boundary system. Inset abbreviations: SMO=Sierra Madre Occidental; B&R = Basin and Range Province; BC=Baja California; TMV=Trans-Mexican Volcanic Belt; MAT=Middle America Trench.

sions may constrain interactions among mantle and lower crustal melts and sediment. Ignimbrites erupted during rifting will provide a detailed volcanic history and chronology for the sedimentary section. Sites in the central Guaymas basin (Fig. 4) will address methanogenesis related to igneous intrusion into organic-rich sediment, a potentially important process in the global carbon cycle that is likely to operate in most sedimented rift systems. Sites in the southern Gulf target magma-poor, tectonic extension during rifting, and the transition from rifting to seafloor spreading. Sites along the Alarcon segment, combined with observations from its landward extension (Umhoefer et al., 2007), will address the extension and subsidence history of this segment as it transitioned from magma-poor, tectonic extension to seafloor spreading.

Complementary to drilling, land studies can constrain the age and composition of rift-related volcanism, and provide additional constraints on basin history.

Woodlark Basin

Key Aspects and Problems to be Addressed: In the Woodlark Basin, westward mid-ocean ridge propagation into continental crust (Fig. 6) allows detailed investigations of continental lithosphere before, during, and after seafloor spreading commences.

Regional Setting and Background: The Woodlark rift is continuous along strike with a seafloor spreading system (Fig. 6). Since Late Miocene time, continental lithosphere of the Papuan Peninsula thickened during Australia-Pacific plate convergence (Davies and Smith, 1971) and has subsequently rifted at some of the highest known rates (Abers, 2001; Wallace et al., 2004). Seafloor spreading initiated after ~200 km of continental extension in the eastern part of the rift basin prior to 6 Ma, and propagated ~800 km to the modern rift-drift transition adjacent to Moresby Seamount (Taylor et al., 1999a). Adjacent to the westernmost spreading segment is an active, north-dipping low-angle (~30°) normal fault that is currently being dissected by igneous intrusions (Goodliffe and Taylor, 2007). Farther west, seismically active rifts (Ferris et al., 2006) continue toward the active metamorphic core complexes of the D'Entrecasteaux Islands, where exposures of high and ultra-high pressure metamorphic rocks suggest exhumation rates of ~10 km Myr^{-1} (Baldwin et al., 2004; Monteleone et al., 2007). The upper plates, separated from the lower plates by shear zones and detachment faults (Hill et al., 1992; Little et al., 2007), consist largely of undeformed mafic and ultramafic rocks. Mylonitic lineations and corrugation surfaces parallel Plio-Pleistocene plate motion vectors (Little et al., 2007).

Proposed Drill Sites: Drilling will address two fundamental issues related to the rift-drift transition in easternmost Papua New Guinea.

1) Rift-drift transition processes. A drilling transect across a nascent spreading segment will address a) the origin of the first magmas at a new spreading center; b) the relationship between magma supply rate and the development of magnetic anomalies associated with seafloor spreading; c) magma-sediment interactions; d) the state of stress at the rift-drift transition; and e) how plate motion accommodation transitions from a low-angle fault to crustal accretion. Drilling will sample the center of the spreading segment and intruded synrift sediment directly to the north and west.

2) Fault patterns and mechanisms responsible for exhuming high and ultrahigh pressure metamorphic rocks from mantle depths ahead of the westward propagating seafloor spreading rift tip, and nature of the rocks above the detachment faults associated with the active D'Entrecasteaux Islands core complexes. Two drilling transects will penetrate sediment and upper plate rocks above the detachment faults, one north of the Prevost Range core complex on Normanby Island (<30 km from the active seafloor spreading tip), and the other north of the Mailolo core complex on northwest Fergusson Island. The active submarine sections of these

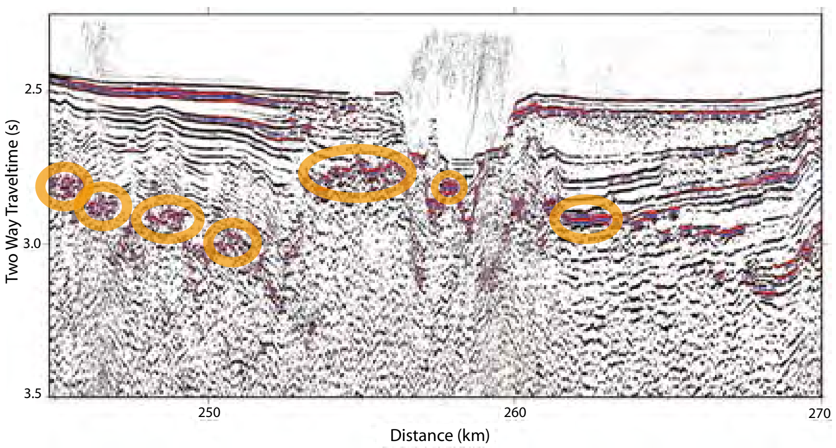

Figure 5. Multichannel seismic profile across the rift graben of the northern Guaymas rift segment of the Gulf of California (see Fig. 4 for location). Sills (circled; identified by reflectivity changes in the sediments they are intruding) drive hydrothermal circulation within the rift valley. Drilling in this vicinity will target thermal and geochemical fluxes as well as geobiological processes including methanogenesis. After Lizarralde et al. (2007).

faults extend below marine sediment that was deposited before and during motion of the hanging wall fault blocks. Drilling will constrain the timing and amount of exhumation directly west of the active seafloor spreading rift and test various models for core complex formation (Abers et al., 2002; Martinez et al., 2001) and for exhumation of high and ultrahigh pressure metamorphic rocks.

North Atlantic Magma-Dominated Margins

Key Aspects and Problems to be Addressed: The conjugate northwest Europe and east Greenland margins (Fig. 7) are characterized by voluminous magmatism associated with the Iceland plume, and their formation may have had significant environmental impact (Eldholm et al., 1989; Eldholm and Grue, 1994; Larsen and Saunders, 1998; Svensen et al., 2004; Storey et al., 2007). The magmatic productivity cannot be explained by simple decompression melting of normal temperature, sub-lithospheric mantle. Three primary competing hypotheses for excessive magmatism are 1) mantle plume with elevated temperatures (White and McKenzie, 1989); 2) small-scale convection at the base of the lithosphere (Mutter et al., 1988; King and Anderson, 1995); and 3) heterogeneities in mantle source composition (Korenaga, 2004).

Regional Setting and Background: The northeast Atlantic conjugate rifted margins show evidence for extensive magmatism including SDRs, igneous intrusions, and high seismic velocity bodies at the base of the crust attributed to magmatic underplating (Fig. 7). The conjugate margins are segmented along strike by the northwest-trending Jan Mayen Fracture Zone and the Bivrost Lineament, which separate the Møre, Vøring, and Lofoten margins and their conjugates at the Jan Mayen microcontinent and off northeastern Greenland (Eldholm et al., 2002). The margin segments are characterized by different tectono-magmatic styles and sediment distributions, with magmatism decreasing from the Vøring segment to the north and south.

Proposed Drill Sites: The overall plan is for two shallow basement penetration transects (eleven holes) located north and south of the Jan Mayen Fracture Zone (Fig. 7), respectively, and one deep sub-basalt hole within the southern transect (Fig. 7). A dip transect (six holes; Fig. 7) to examine temporal variability of magmatism extends across the conjugate margin segment pair of central Møre/Jan Mayen Ridge. Each hole is well characterized by high quality seismic reflection data. A strike transect to sample breakup-related volcanic rocks in different margin segments as well as facies units extends along the Norwegian margin. The main segments to be drilled include 1) the central Møre margin (i.e., the location of the dip transect); 2) the southern Vøring margin (transform margin related volcanism); 3) the northern Vøring margin (voluminous volcanic complex); and 4) the southern Lofoten margin (small volcanic complexes). The deep hole—to examine temporal variability of magmatism and the nature, environment, and implications of the rift and early breakup magmatism—will be a reoccupation of a landward site on the Møre-Jan Mayen Ridge conjugate margin transect. Specific issues to be addressed by drilling are 1) melt sources and melting conditions, 2) timing of magmatism, 3) spatial and temporal variations of volcanism, 4) eruption environment and vertical movements, 5) along-axis variations in melt production, and 6) consequences of excessive magmatism for environmental change.

Overall, geophysical (including two-dimensional, three-dimensional, and wide-angle seismic) and geological (including DSDP, ODP, and commercial drilling) data sets for the North Atlantic LIP are comprehensive and of high quality.

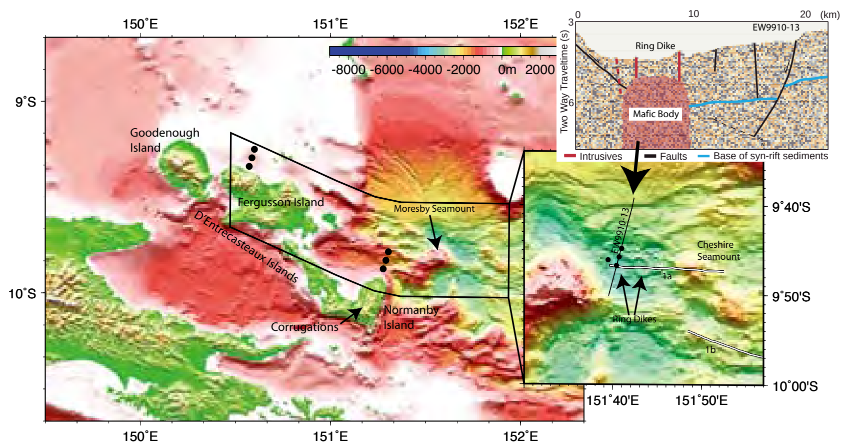

Figure 6. Western Woodlark Basin and easternmost Papuan Peninsula showing the locations of proposed drill sites (black dots). Inset (right) shows details of the rifting-spreading transition.

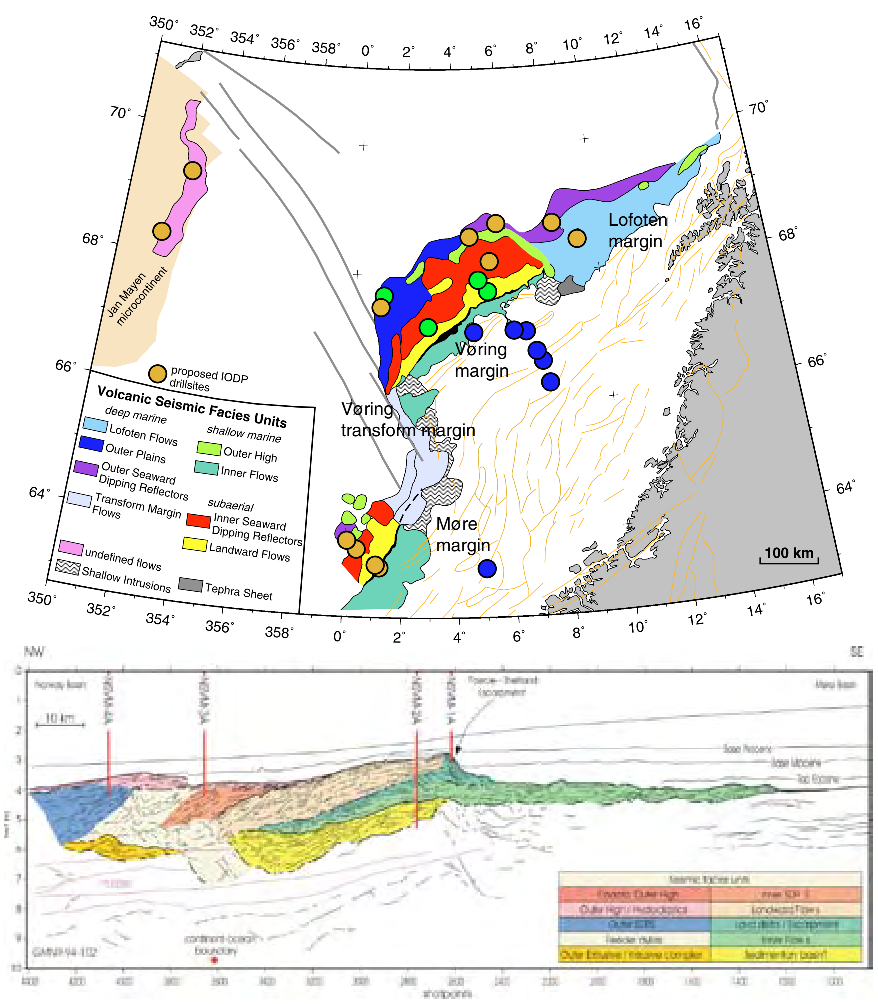

Figure 7. Upper: Distribution of volcanic seismic facies units on the mid-Norwegian margin (from Berndt et al., 2001), proposed IODP sites, and selected boreholes (DSDP/ODP drill sites in green circles; commercial boreholes in blue circles). Lower: Interpreted seismic profile across the Møre Margin (location above), revealing several distinct volcanic facies units (Planke and Alvestad, 1999; Planke et al., 2000).

Newfoundland-Iberia Rift

Key Aspects and Problems to be Addressed: The Iberia and Newfoundland margins (Fig. 8) lack extensive magmatism; they are hyper-extended, characterized by polyphase and diachronous rifting, detachment faulting, and mantle serpentinization and unroofing (Pérez-Gussinyé and Reston, 2001; Reston, 2005; Tucholke et al., 2007). Thin sedimentary cover makes tectonic targets uniquely accessible to drilling. Key problems concern the timing of rifting (along and across the margins), breakup, and the onset of seafloor spreading; the mechanism(s) of extreme crustal thinning; the role of detachment faulting in mantle unroofing; and the nature of basement within the continent-ocean transition.

Regional Setting and Background: During Late Jurassic and Early Cretaceous periods, rifting localized between Newfoundland and Iberia, and the two separated. Breakup propagated from the Central Atlantic northward (Srivastava et al., 2000), but critical details remain controversial. In the south of the Newfoundland-Iberia region, seafloor spreading anomaly M3 (128–130 Ma; Gradstein et al., 2004) has been identified (Srivastava et al., 2000; Russell and Whitmarsh, 2003), whereas in the north, M0 (124.5–125 Ma) appears to be the oldest anomaly. However, some evidence indicates that pre-spreading rifting continued into late Aptian time (~112 Ma; Boillot et al., 1987; Reston, 2005), supporting the idea that the earliest 'seafloor spreading' magnetic anomalies may have originated from unroofed mantle rather than igneous crust formed at a focused spreading center.

Such uncertainties in timing of key events preclude a thorough understanding of dynamic processes because neither rates nor spreading mechanisms are yet accurately known. Another outstanding problem is how the crust was thinned to only a few kilometers, challenging many tenets of lithospheric rheology and isostasy. Some combination of polyphase faulting and DDS seems likely, but the relative importance of the two is controversial (Davis and Kusznir, 2004; Reston, 2007). Similar problems characterize other rifted margins—the South Atlantic (Moulin et al., 2005), Northwest Australian (Driscoll and Karner, 1998), the Labrador Sea (Chian et al., 1995), and the Parentis basin (Pinet et al., 1987).

Proposed Drill Sites: A key objective is to determine the timing of events, which is needed for a quantitative understanding of the rates of processes associated with final thinning, crustal separation, lower crust and mantle exhumation, the onset of mantle melting, and seafloor spreading. Complete sedimentary sections on both margins are required to achieve this objective (Fig. 8). Well defined synrift wedges above a probable detachment (S) on the Iberia (Galicia Bank) margin and relatively thin sedimentary cover on the conjugate Newfoundland (Flemish Cap) margin provide unique opportunities to establish the timing of events. Another major objective is to test competing ideas on how lithosphere deforms during the final thinning phase of extension leading to exhumation of lower crust and mantle. Thinned continental crust must be sampled at key locations to achieve this objective (Fig. 8).

Flemish Cap. Drilling will help determine 1) the role of hypothesized concave-down faults in exhumation of lower crust and upper mantle during late breakup; 2) the interplay among tectonic, magmatic, and serpentinization processes in hyper-extended rift environments; 3) whether continental crust was removed completely amagmatically; 4) if initial melt products were distributed asymmetrically, with more melt on the Newfoundland side; 5) when and how rifting transitioned to seafloor spreading; 6) controls on the localization of deformation into serpentinized shear zones; and 7) when asymmetries between Galicia Bank and Flemish Cap developed. The most landward sites lie on the continental slope where continental crust is <5 km thick, and will provide key information on rock types where extreme thinning with little to no upper crustal extension is observed in seismic sections. The sites will sample as much stratigraphy as possible to constrain timing as well as penetrate into basement rocks. The most seaward sites will test competing hypotheses for the formation of transition zone crust, mantle exhumation, and formation of anomalously thin oceanic crust.

Galicia Bank. Drilling will recover complete sedimentary sections at two sites that will help establish the timing and geometry of fault block movements associated with the formation of the 'S' reflection and emplacement of the peridotite ridge just prior to seafloor spreading (Fig. 8). One site (GBB-7A) will penetrate the 'S' reflection, hypothesized to represent a regional detachment surface. Data from overlying strata will constrain the timing of any motion along the surface and dip angles during motion. Coring the hypothesized detachment will reveal deformation above and below the fault while it was active. Another site (GBB-8A) will penetrate a basin and the eastern flank of the peridotite ridge. While the top of the ridge has been sampled, little is known about its internal structure and mode of formation, and when the ridge was exposed at the seafloor.

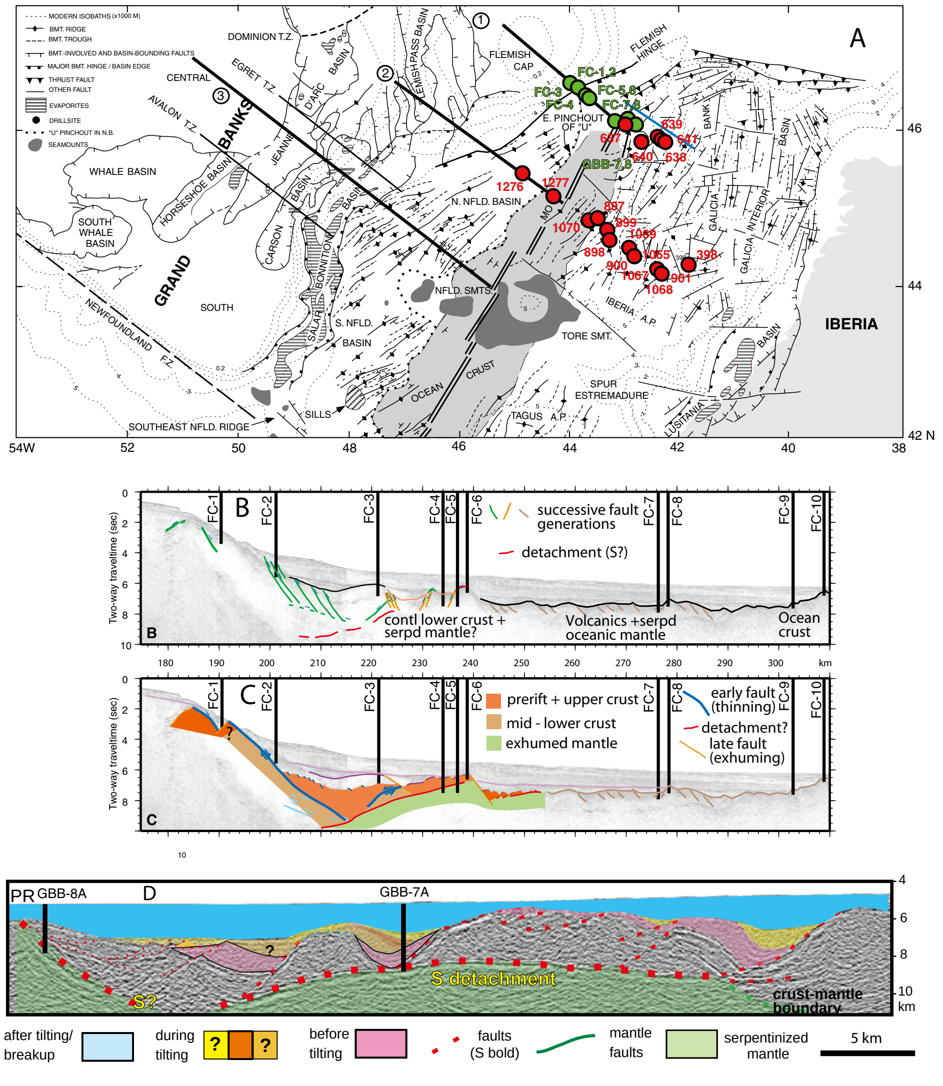

Figure 8. Summary of proposed drilling on the conjugate Newfoundland-Iberia hyper-extended margins. [A] Reconstruction of Iberia to Newfoundland at magnetic anomaly M0 time (124.5–125 Ma) (Srivastava et al., 2000). Red numbered dots are drill sites from ODP Legs 103, 149, 173, and 210. Green lettered dots are proposed drill sites in proposal 692 (FC-X) and proposal 657 (GBB-X). FC-8A to FC-10A are on crust younger than M0 and therefore are not shown. Thick lines labeled 1, 2, and 3 are the main SCREECH (Study of Continental Rifting and Extension of the Eastern Canadian shelf) transects along which both seismic reflection and refraction data were collected. Location of profile in part [D] is shown in blue. Figure adapted from Tucholke et al (2004). [B], [C]. Alternative interpretations of SCREECH 1 (Hopper, pers. comm.) showing location of drill sites which will test these and other models of breakup. [D] Depth image of Galicia margin (Reston et al., 2007) showing hypothesized detachment fault S beneath block-bounding faults. Drilling here will constrain nature and mechanics of S, age of overlying synrift wedges and evolution of mantle peridotites.

South Atlantic Margins

Key Aspects and Problems to be Addressed: Large data sets from the conjugate margins of the South Atlantic suggest that the crust here has been thinned more than can be explained by the observed faults. Drilling of well imaged synrift and early postrift sediment infill of marginal sag basins will provide critical information on timing and facies for understanding margin evolution, including the cause of the extension discrepancy.

Regional Setting and Background: Rupture between South America and Africa propagated from south to north in the Late Jurassic and Early Cretaceous time as the South Atlantic Ocean formed. The resulting South Atlantic passive margins can be divided broadly into three provinces. The first province, the South of Walvis, voluminous magmatism led to ~100-km-wide SDRs within the crust along both the Argentine and Namibian conjugate margins. The second province, the North of Walvis Ridge—the rifted margin of eastern Brazil and its conjugate Angola, Congo, and Gabon margins (Fig. 9)—also experienced volcanism during breakup, but

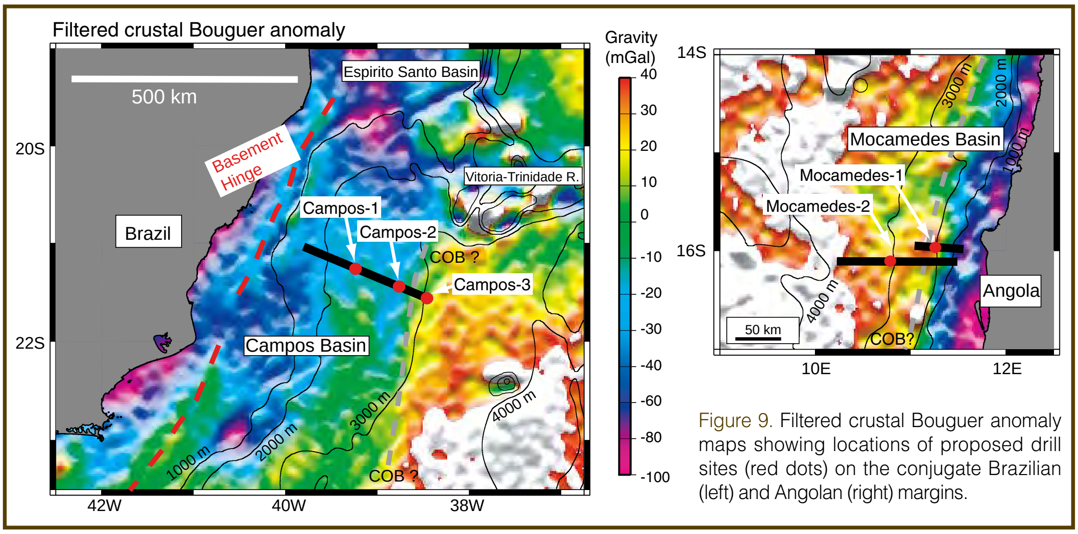

Figure 9. Filtered crustal Bouguer anomaly maps showing locations of proposed drill sites (red dots) on the conjugate Brazilian (left) and Angolan (right) margins.

not sufficiently voluminous to form SDRs. Synrift and postrift sedimentation was dominated by Aptian salt, carbonate platforms, and clastic sediment. The third province, the conjugate rifted margins of the equatorial Atlantic, are narrow compared to the hyper-extended margins to the south. Synextensional sag basins, where salt was deposited and mobilized, are found in both the Campos Basin offshore Brazil and the Kwanza Basin offshore Angola. The relative timing of Early Cretaceous synrift volcanism, evaporite deposition, and onset of seafloor spreading are controversial. The seaward edge of the Aptian salt basin may lie on thick SDR wedges (Jackson et al., 2000), implying that salt was deposited after final continental breakup; volcanic edifices in the continent-ocean transition zone probably acted as barriers between the episodically dry marginal basin and the open ocean where new oceanic crust was forming. However, Aptian salt is also abundant in the vicinity of the Congo Fan, where no thick igneous crust or SDRs are imaged in the continent-ocean transition zone. Even in the absence of a potentially bounding basement high, the seaward limit of autochthonous salt appears to lie close to the inferred landward limit of oceanic crust (Marton et al., 2000). Evaporites may even have been deposited on serpentinized mantle in the continent-ocean transition zone (Moulin et al., 2005). Mantle exhumation prior to continental breakup is well characterized from the Newfoundland-Iberia rift, and conceptual models show how continental mantle may be exhumed by low-angle normal faults (Lavier and Manatschal, 2006). However, whereas mantle was exhumed well below sea level along the Newfoundland rift (Tucholke et al., 2007), the continent-ocean transition zone of the central South Atlantic appears to have been close to sea level prior to breakup.

Proposed Drill Sites: Drill sites in the Campos Basin offshore Brazil and the Moçamedes Basin offshore Angola will establish the tectonic setting of marginal basin formation in the central South Atlantic (Fig. 9). Two sites in the Campos Basin lie at the seaward end of a sag basin; drilling will establish the timing and environment of Aptian salt basin formation. A third site on the Brazilian margin, just seaward of the continent-ocean transition, will sample the oldest oceanic crust. In the Moçamedes Basin on the conjugate Angolan margin, basement will be penetrated where a low-angle fault appears to have ex-humed continental mantle. In total, combined site survey characterization and drilling of the sites will investigate 1) the applicability of conceptual models developed from Newfoundland-Iberia rift characteristics to South Atlantic margins; 2) the age of the first oceanic crust, and relative timing of both continental breakup and the deposition of pre-salt sag sequences; 3) the nature and composition of the crust on which pre-salt sequences were deposited; 4) interpreted exhumed continental mantle in the continent-ocean transition zone; 5) the possible existence of top-basement detachment faults; and 6) synrift and early postrift subsidence along a geophysical transect of the conjugate margins.

NW Australian Magma-Dominated Margin

Key Aspects and Problems to be Addressed: The northwest Australian magma-dominated (rifted) margin (Fig. 10) is segmented, and igneous rock volumes vary considerably along strike, without clear evidence for a related mantle plume (Mutter et al., 1988; Hopper et al., 1992; Symonds et al., 1998; Planke et al., 2000). This makes the margin a strong candidate to test the edge-driven/small-scale convection hypothesis for generating excessive magmatism. Temporal and along-strike variations in melt production and temporal and spatial relationship(s) between rifting and magmatism are secondary objectives.

Regional Setting and Background: The western Australian margin can be divided into four main segments separated by major fracture zones: Argo, Gascoyne, Cuvier, and Perth (Fig. 10). The entire margin exhibits breakup magmatism in the form of sills, SDRs, hyaloclastic buildups, and magmatic underplating that formed during Callovian (~163 Ma) Argo margin breakup and subsequent Valanginian (~138 Ma) Gascoyne, Cuvier, and Perth margin breakup (Planke et al., 2000; Symonds et al., 1998). The conjugate margins have been subducted or obducted. Two main hypotheses—mantle plume (White and McKenzie, 1989) and edge-driven/small-scale convection (Mutter et al., 1988; King and Anderson, 1998; Korenaga, 2004)—have been proposed for the formation of these massive igneous constructions (Coffin et al., 2002; Ingle et al., 2002; Müller et al., 2002). Because it cannot be convincingly tied to a well established hotspot track, the western Australian margin is a highly promising candidate for testing alternative hypotheses for magmatic margin formation (Planke et al., 2000).

If a plume was involved in the formation of the western Australian margin, then the Wallaby Plateau-Zenith Seamount province probably represents the post-breakup track of the plume. This province extends some 1200 km from the continent, across a continent-ocean transition zone likely associated with composite continental and magmatic plateaus, and into a normal ocean basin, providing an ideal opportunity to examine variations in continental contamination in time and space. Documenting the presence or absence of a geochemical plume signature within igneous basement of the Cuvier margin will therefore be a critical complement to previous and ongoing studies of the North Atlantic igneous province.

Proposed Drill Sites: The objectives are as follows: 1) to distinguish between an edge- vs. plume-driven cause for magmatism along a rifted margin; 2) to examine rift and breakup duration, and subsidence history; 3) to investigate the formation and crustal nature of marginal plateaus; 4) to understand the temporal development of multiple SDR wedges; and 5) to determine age, volume, duration, and environment of volcanism. To address these objectives, a five-hole transect across the southern Cuvier margin and the Wallaby Plateau as well as a reference hole in similar age oceanic crust of the nearby Cuvier Abyssal Plain are envisioned (Figs. 10 and 11). The holes will sample i) multiple SDRs across the margin; ii) the Wallaby Plateau, and iii) oceanic crust. The petrology and geochemistry of the recovered rocks will be used to determine melting conditions, magma reservoir type (asthenosphere, lithosphere, plume), and contamination by continental lithosphere. Precision age determinations will constrain the temporal and spatial evolution of the magma source. Regionally, the west Australian margin is relatively well investigated by seismic surveys, dredging, and commercial drilling on the continental shelf.

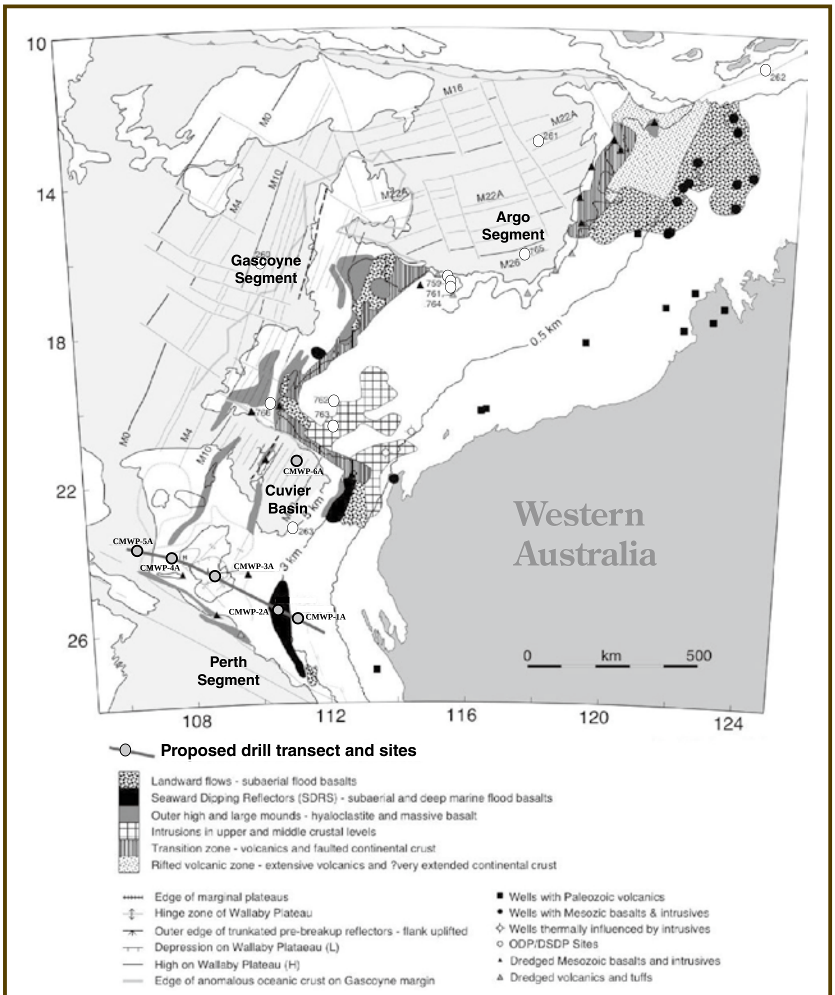

Figure 10. Regional setting of northwest Australian margin with proposed IODP sites.

We now recognize that 2-D seismic technology does not meet the challenge of contemporary research in rifting and breakup, which are fundamentally 3-D processes. As part of its strategy in investigating rifting and breakup, the IODP should integrate acquisition and interpretation of 3-D seismic reflection data with overall program planning.

Land-based geological research has been a valuable complement to ocean drilling and marine geophysics at several rifted margin systems. The Gulf of California is a good example of a rift system that is only partly submerged. Similar opportunities are offered by the Woodlark Basin, where metamorphic core complexes and other rifting components are exposed on islands, and in the North Atlantic LIP, where flood basalts and related rocks crop out in the British Isles

Essential Complements to Drilling

To date, seismic studies of rifted continental margins by the academic community have been almost entirely 2-D, comprising widely spaced profiles relative to the lateral scale of faults and stratigraphic variations.

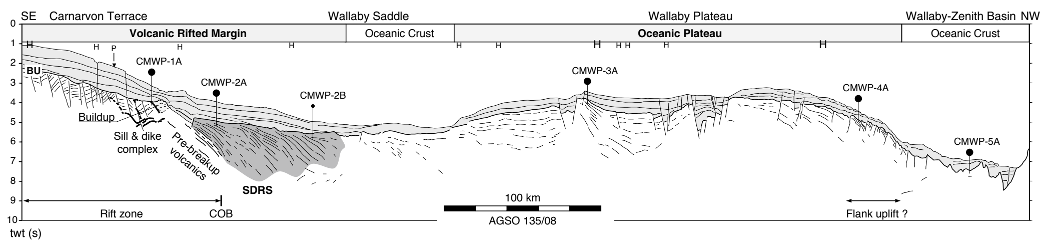

Figure 11. Interpreted seismic profile across the southern Cuvier margin and Wallaby Plateau with proposed IODP sites. COB: continent-ocean boundary; BU: breakup unconformity. See Fig. 10 for location of profile.

Figure 12. Early Tertiary flood basalt sequence in eastern Greenland associated with rifting and breakup between eastern Greenland and northwestern Europe, highlighting opportunities along some margins for synergetic onshore-offshore studies.

and Greenland (Fig. 12). The study of rift systems now exposed on land in mountain belts is another way that the advantages of field geology can contribute to the study of rift systems, as exemplified by comparisons between the Alpine Tethys rift system exposed in the Alps (Fig. 13) and the Iberia/Newfoundland rift system (Manatschal, 2004; Lavier and Manatschal, 2006).

Modeling the processes of continental rifting is increasingly important for making predictions that can be tested by drilling. Forward dynamic models now provide insights into magmatism accompanying breakup (Boutilier and Keen, 1999; Nielsen and Hopper, 2004) as well as primary controls on passive margin width, symmetries/asymmetries, and evolution from wide, diffuse rifting into narrow, localized rifting resulting in the formation of passive margins (Huismans and Beaumont, 2003, 2007; Lavier and Manatschal, 2006).

The study of continental breakup and sedimentary basin formation offers opportunities for significant collaboration between the hydrocarbon industry and the IODP. During the workshop, interest in collaboration was highest for the conjugate rifted margins of the South Atlantic.

Technical Requirements

COBBOOM will require a combination of existing IODP technology and the development of new technology. Proposed deep and challenging drilling will require the use of both riser and non-riser drills. Where water depths are less than 2500 m, we anticipate using riser capability, casing, and mud circulation to increase hole stability and improve the likelihood of deep penetration. However, some holes have the goal of sampling highly stretched continental crust and upper mantle beneath relatively thin sediment cover and in much deeper water. For such holes, ultra-long drill strings deployed in a non-riser mode and supported by extensive casing programs will be required.

Improved methods of core orientation in sedimentary and crystalline rocks will improve our ability to relate microstructures and faults in the core to the strain distribution in the rifting system. In active rift environments, borehole observatories will be used to monitor the presence and pressure of fluids in faults active during rifting. Technology currently being developed to monitor microseismicity near the boreholes will assist in understanding its relationship to fluid pressure variations.

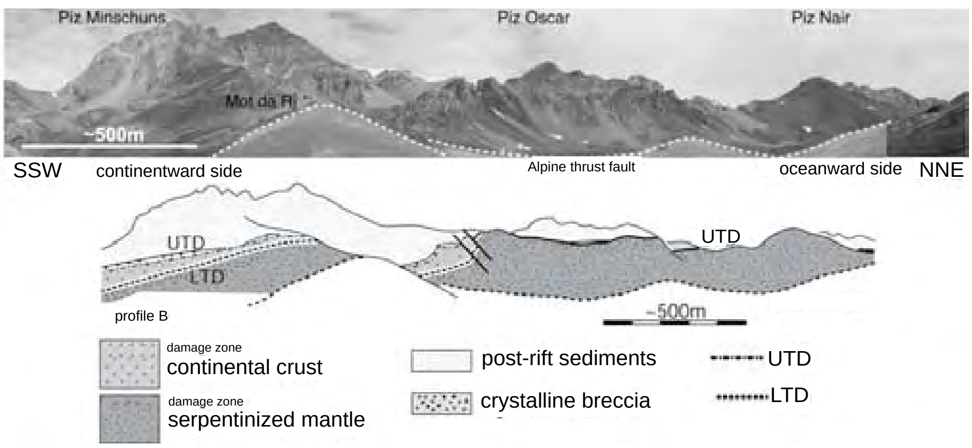

Figure 13. Exposed continent-ocean transition in the Tasna nappe in southeastern Switzerland (after Florineth and Froitzheim, 1994). Onshore analogs have contributed significantly to understanding hyper-extended margin development. UTD: Upper Tasna detachment; LTD: Lower Tasna detachment.

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Exploring Subseafloor Life with the Integrated Ocean Drilling Program

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Introduction

Deep drilling of marine sediments and igneous crust offers a unique opportunity to explore how life persists and evolves in the Earth's deepest subsurface ecosystems. Resource availability deep beneath the seafloor may impose constraints on microbial growth and dispersal patterns that differ greatly from those in the surface world. Processes that mediate microbial evolution and diversity may also be very different in these habitats, which approach and probably pass the extreme limits of life. Communities in parts of the deep subsurface may resemble primordial microbial ecosystems, and may serve as analogues of life on other planetary bodies, such as Mars or Europa, that have or once had water.

Cell concentration estimates suggest remarkably abundant microbial populations in subseafloor sediments (Whitman et al., 1998; Parkes et al., 2000), but current models do not account for their possible impact on global biogeochemical cycling. Furthermore, we lack fundamental knowledge of microbial community composition, diversity, distribution, and metabolism in subseafloor environments. Exploration of this system presents a rich opportunity to understand microbial communities at Earth's extremes. Microbes in different subseafloor environments often encounter and must survive conditions of high pressure, high temperature, and extreme starvation. The limits of subsurface life are not yet known in terms of any environmental properties, including depth, temperature, energy availability, and geologic age; however, it is known that subseafloor microbes play a significant role in chemical reactions that were previously thought to have been abiotic, including iron and sulfur cycling as well as ethane and propane generation (Hinrichs et al., 2006). Some subseafloor communities probably derive food (electron donors) without sunlight (Jørgensen and D'Hondt, 2006). In addition, while molecular analyses and cultivation experiments demonstrate a surprisingly high diversity of microbial life in the subseafloor (Reed et al., 2002; Inagaki et al., 2003, 2006; Teske, 2006; Webster et al., 2006; Batzke et al., 2007), the relative abundances and roles of *Archaea*, *Bacteria*, *Eukarya*, and viruses remain largely unknown. In short, subseafloor life constitutes one of the least explored biomes on Earth and deserves intense exploration.

The Integrated Ocean Drilling Program (IODP) provides researchers with tremendous opportunities to better understand the abundance, activity, diversity, and limits of deep subseafloor microbial communities through drilling expeditions. A workshop titled "Exploration of Subseafloor Life with IODP" was convened in October 2006 to solicit recommendations and guidance from a broad community of scientists and to address scientific issues and technical challenges for exploring microbial life in the deep subseafloor. The ninety diverse workshop participants included molecular biologists, microbiologists, microbial ecologists, geologists, biogeochemists, drilling experts, and engineers.

Breakout sessions were focused on four key scientific areas: (1) biogeography, (2) genes, cells, populations, and communities, (3) habitability, and (4) technology. The principal conclusions of these breakout groups were as follows:

Biogeography: Four aspects of biogeography were considered particularly important. The first is a thorough characterization of the full range of deep subsurface habitats and their microbiota including deep subseafloor communities that are controlled by surface inputs (for example, via sediment accumulation) and their changes with age and depth. They also include microbial communities that derive their energy from non-photosynthetic processes (e.g., thermogenesis of organic compounds, subduction zone processes, serpentinization, and radiolysis of water) and basaltic environments deep beneath the seafloor. The last is potentially Earth's largest habitat by volume, but its significance as a habitat for microbial life has yet to be confirmed. Second, spatial and temporal controls on diversity need to be explored through (1) detailed fine-scale analysis of appropriately stored cores from previously drilled holes, (2) new drilling expeditions that target contrasting sedimentary environments, and (3) institution of deep subseafloor microbial observatories. Such studies will identify evolutionary controls on diversity and go beyond current surveys of biodiversity changes with depth and habitat. Third, we also need to know the mechanisms and rates of evolution under potentially slow growth, low predation, and severe energy limitation conditions. Do these situations select for novel metabolic and life history strategies? Finally, the extent to which the deep biosphere is generally connected or isolated from the surface biosphere is unclear. Is there a subsurface community unique to the deep biosphere? Does horizontal spreading of microbes cause the same biogeochemical zones to contain the same communities in different oceans, or are there barriers to dispersal?

Genes, cells, populations, and communities: The workshop participants recommended that microscopic observations of sediment and rocks should be expanded to include modern cell staining procedures that maximize biological information. In combination with studies of nucleic acids and organic biomarkers, such direct counts can provide information on the abundance, distribution, and extent of microorganisms in the subseafloor biosphere. Relatively detailed information on microbial populations can be gathered by employing specific microscopic techniques that provide fundamental information about the phylogenetic status and activity of individual cells. Because viral populations have the potential to play important roles in cell death and in horizontal transfer of genes between microorganisms, efforts should also be made to assess the abundance of viruses in both sediment porewater and crustal fluids. Studies of microbial abundance will answer major questions regarding the extent of the subseafloor biosphere, per-cell rates of microbial activities, and the roles of specific populations in major biogeochemical cycles. In addition, with rapid progress in molecular microbial ecology methods, it is now possible to determine the overall genetic potential of microbial communities and to link this potential to specific gene function and expression. This combination of approaches will provide rich information about subseafloor microbial genes, cells, populations, and communities.

Habitability: Subseafloor sediments and crust comprise two of the largest habitats on Earth. Exploring these habitats poses three major challenges for the biogeochemical and geomicrobiological scientific community. The first of these challenges, defining and mapping the limits to habitability in deep subseafloor sediments and crust, was deemed by the breakout group participants to be of highest priority. These limits are set by a variety of physical and chemical properties, such as temperature, availability of energy and nutrients, pH, pressure, water availability, and salinity. Mapping global distributions of physical properties, concentrations, and fluxes of both reductants and oxidants that provide a hospitable environment for microbial activity in the subseafloor ocean should be an obvious product of a concerted scientific drilling effort. The second critical challenge is the detection of life and the consequences of microbial activity, especially in low energy systems. The third challenge is to determine the role of deep subseafloor habitats in biosphere-geosphere coupling (e.g., how the subseafloor biosphere affects global biogeochemical cycles). Thorough and quantitative descriptions of key environments, microbial activities, and mass fluxes are required. The geological and biological processes that control transitions in states of habitability and that fuel growth and survival of microbial communities in deep subseafloor environments remain to be determined, but they can be realized through appropriate IODP projects. The opportunity to characterize these transitions with high resolution sampling across a variety of deep subseafloor environments should be pursued by using a broad array of potential microbial signatures—pore water metabolic products, alterations of elemental isotope distributions, enzymatic activities, RNA, and intact polar lipids.

Technology: A number of issues related to technology were discussed. The primary objective was to assure that specific procedures of coring, sample handling, archiving, and routine measurements would be maintained to facilitate microbiological characterization of the deep biosphere. The participants recognized on-going efforts that have been undertaken to facilitate coring and sample handling for study of subseafloor life. Workshop recommendations were intended to build on this existing framework. They included the establishment of an IODP microbiology legacy sampling protocol that would be essential to further studies of the deep biosphere and to facilitate interdisciplinary investigations among IODP scientists. All data generated as part of this legacy sampling should be integrated with the existing IODP database structure, and more microbiological analyses must be added. The IODP is clearly the best vehicle to gain an understanding of the microbial life of the deep biosphere, though appropriate modifications of existing sampling and analytical protocols may be necessary.

Efforts must be made to develop and refine new shipboard and *in situ* technologies, with one major focus being on CORKs (circulation obviation retrofit kit). CORK technology can provide a platform for culturing active microbial members of the population *in situ* as well as continual access to subsurface porewater for continuous biogeochemical monitoring of microbial activity within the subseafloor.

Scientific Objectives

Several major scientific objectives were described by multiple working groups as ideally addressed by IODP capabilities. These include (1) discovering the limits of life and habitability on Earth; (2) determining the extent and nature of deep subseafloor life; (3) identifying the fundamental processes that control the dispersal and evolution of subsurface life; and (4) quantifying the rates and consequences of interactions between the deep subseafloor biosphere and the surface world.

Limits of Life and Habitability on Earth

There are very few natural environments on Earth's surface where life is absent; however, limits to life are expected in the subsurface world. Consequently, deep drilling of the ocean crust and sediments is uniquely positioned to access and explore the physical and chemical limits to life.

Transitions between states of habitability, as shaped by transitions in environmental properties, are laid out over extensive spatial and temporal scales in the subsurface

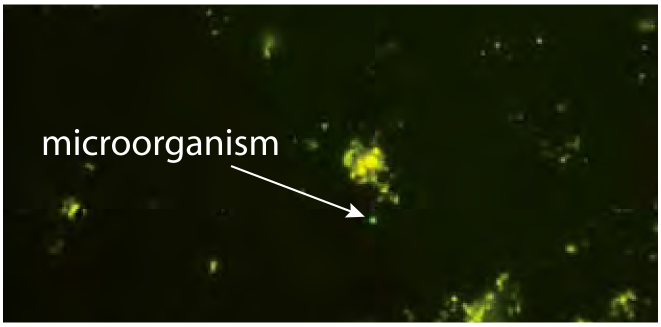

Figure 1. Microorganism from sediment deep beneath the Arctic seafloor (IODP Leg 302). The microbe glows because it has been stained with a fluorescent dye (SYBR Green) that preferentially binds to DNA. Photomicrograph from David C. Smith..

realm. The opportunity to characterize these transitions with high resolution sampling, across a variety of subseafloor environments, is unparalleled for characterizing the fundamental constraints on life. Deep subseafloor drilling is uniquely capable of realizing this potential.

The surface and subsurface realms differ fundamentally in their potential to refine our concept of habitability. The surface world is extensively inhabited. It is characterized by abundant flows of energy. Its uninhabitable spaces are rare. They principally result from dramatic extremes of temperature or aridity, and they typically begin at sharp spatial and temporal transitions from abundantly inhabited spaces. The abrupt aspect of these transitions is incongruent with the nature and resolution of sampling required to refine our sense of habitability and the limits to life. The deep subsurface environment contrasts these characteristics in several respects that offer significant promise for characterizing fundamental constraints on life and habitability. The current state of the art in ocean drilling virtually ensures that the limits of habitability and life will be breached with respect to physical, chemical, and energetic constraints, both individually and in combination. For example, energy flow in subseafloor settings is often orders of magnitude lower than in the surface world (D'Hondt et al., 2002). Subseafloor gradients in environmental conditions and biological states occur over distances that permit highly resolved sampling.

High temperature provides an obvious example of a limit to life and habitability that can be effectively explored through deep-ocean drilling. The presently accepted upper temperature limit for life is 121°C (Kashefi and Lovley, 2003), although higher temperature limits have been inferred by a small number of studies. Drilling into subseafloor sediments, igneous rocks, and hydrothermal deposits with temperatures that span the range of 100°C–250°C can be used to provide data that may determine upper temperature limits for life.

An additional parameter that undoubtedly limits the occurrence of life is the availability of energy (electron donors and electron acceptors). Subseafloor environments include environments where energy availability is probably too low to maintain life, and environments where life-sustaining fluxes of electron donors (food) may be independent of photosynthesis and the surface world. In order to characterize these environments, their potential inhabitants, and their control on the occurrence of life, these chemical constraints should be studied in a broad range of environments, including, but not limited to, sediments with very low organic content, deep crustal rocks, and subseafloor regions of active serpentinization.

Environmental limitations on cell density and community complexity may also include the mineralogy of sediments and sub-sediment rocks, interaction between cells and minerals, surface area, porosity and permeability, minimum pore size, and the availability of water.

Extent and Nature of Life in the Deep Subseafloor

The discovery of a diverse and active subseafloor microbial community in deep sediments and crustal rocks has fundamentally changed our perception of life on Earth, yet, the extent and nature of this subsurface life remains largely unknown. To address this issue, information on the abundance, diversity, and activities of *Archaea*, *Bacteria*, *Eukarya*, and viral populations needs to be elucidated.

Abundance—Microbial cells are widespread and often abundant in subseafloor sediment (Parkes et al., 2000) (Fig. 1), but the geographic distribution, composition, and total biomass of subseafloor life is largely unknown, because major provinces of ocean sediment and crust have never been examined for life, and many categories of organisms (archaea, eukaryotes, viruses) have never been sought in subseafloor samples. Routine microscopic observations of sediment and rocks should be expanded to consistently include direct cell counts. Further information on subseafloor populations can be gathered with microscopic techniques that provide phylogenetic and activity information (such as fluorescent *in situ* hybridization [FISH], catalyzed reporter deposition [CARD]-FISH, 5-cyano-2,3-ditolyl tetrazolium chloride [CTC], and live/dead staining). To examine viral populations, which have the potential to play important roles in cell death and horizontal gene transfer, efforts should be made to assess their presence in the porewater of sediments (as in Breitbart et al., 2004) and in crustal fluids. Detectable viral populations should be sequenced or tested for an effect on sediment organisms. In addition, efforts to explore the existence and abundance of eukaryotes in sediment and oceanic crust need to be made. The examination of microbial abundance will help answer major questions regarding the extent of the subseafloor and the rate of activity per cell in biogeochemical cycles. These results will serve as a major guide for microbiological investigations of subseafloor sediment and basalt.

Diversity—Microorganisms are the most abundant and diverse life forms on the planet and are the fundamental drivers of global biogeochemical cycles. Despite their ubiquity, surprisingly little is known about their diversity in the subseafloor, where sediments and basalt are key environments for studying microbial populations and community structures. Many important questions can only be solved by first understanding what microorganisms are present and what functional roles they serve in their communities. Given the combinations of extreme physical and chemical conditions, many of which are only found in the subseafloor (high pressure, low carbon, etc.), this environment is likely to contain assemblages of endemic microorganisms well-adapted to these conditions. Therefore, the subseafloor represents a rich and potentially novel source of genetic material for study and for mining for novel enzymes and enzymes adapted to extreme conditions that can be applied to a wide variety of biotechnological applications.

To understand subseafloor diversity, it will be necessary to conduct surveys of appropriate phylogenetic (16S rRNA genes (Fig. 2) and 18S rRNA genes) and functional gene markers. A variety of methods exist for such microbial diversity analyses (denaturing gradient gel electrophoresis (DGGE), terminal restriction fragment length polymorphism (T-RFLP), clone libraries, and tag sequencing); individual investigators should choose the method that is most appropriate based on their specific questions, equipment, and available resources. Unusual and rare microorganisms are to be expected in the deep subsurface, and they may require novel 16S rRNA sequencing approaches for their detection (Sogin et al., 2006). In addition, other markers for phylogenetic diversity should also be considered (e.g., *recA*, *gyrase*). While phylogenetic approaches are useful for understanding diversity, they do not provide a direct understanding of function. To better investigate the genetic potential of the subseafloor and the physiological roles of its inhabitants, a suite of investigations would need to be integrated. Molecular approaches include laser capture microdissection (a method for extracting a single cell), which can be coupled to whole genome amplification to map the entire genome of individual cells (Podar et al., 2007). In addition, mRNA amplification for gene expression profiles may be of particular importance for use in low biomass environments.

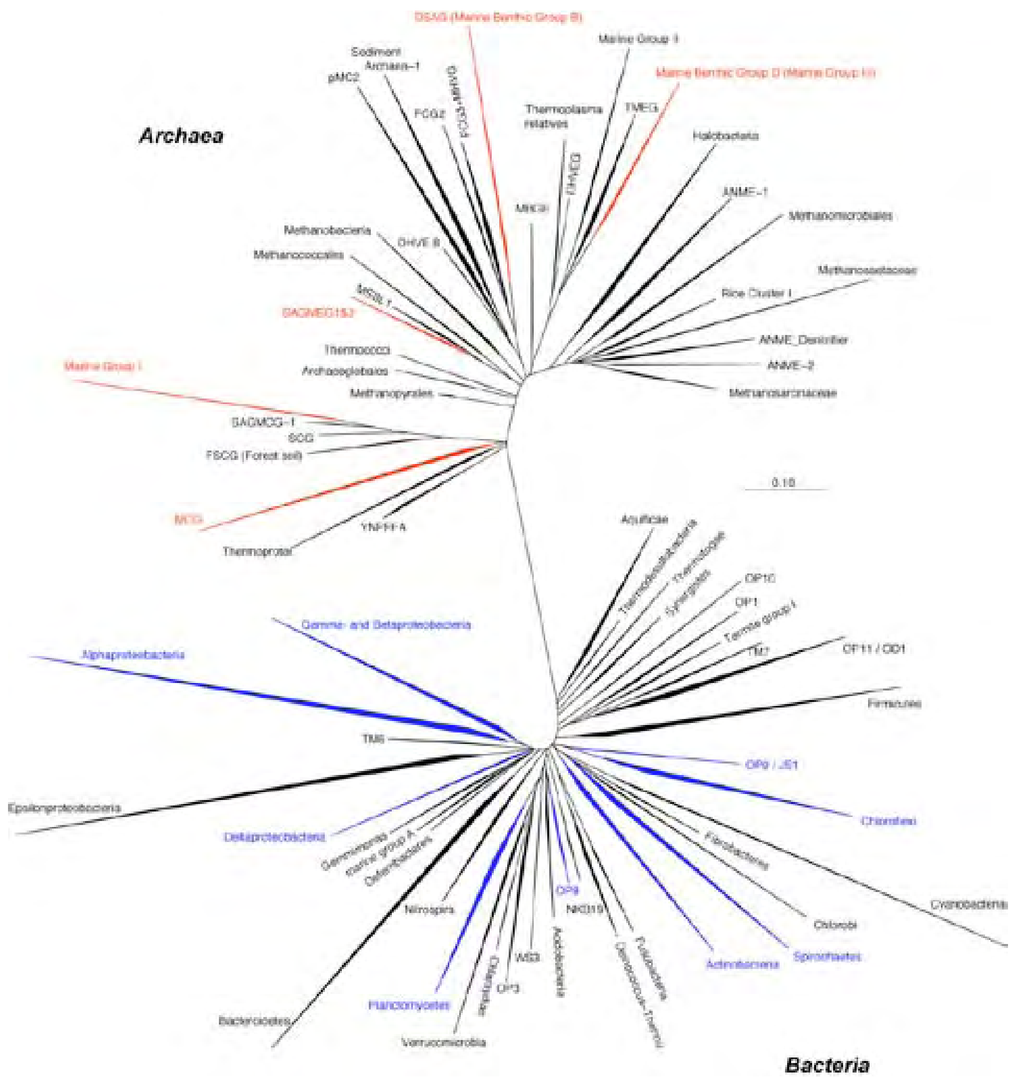

Figure 2. Phylogenetic tree of the domains Archaea and Bacteria based on 16S rRNA gene sequences. Red and blue lines respectively represent branches of archaea and bacteria that have been frequently detected in deep subseafloor sediments. The scale bar indicates the expected number of changes per nucleotide positions. Sequence data were analyzed with the ARB software package (Ludwig et al., 2004).

The application of genomic methods to the study of microbial communities directly from the environment (e.g., metagenomics) also represents a range of powerful new approaches. Initial forays into the generation of metagenomic data might best be performed on low diversity environments of at least moderate biomass. This would increase the ability to obtain a larger contiguous sequence from shotgun sequencing and assembly. The creation of genomic libraries also represents an important form of archiving, since these libraries represent a snapshot of the environment from which they were constructed and can be mined by multiple investigators over time.

Metagenomic data, particularly a deep coverage reference metagenome, would create a critical resource for furthering the application of post-genomic methods designed to investigate gene presence or absence (DNA), transcription (mRNA), and translation (protein). For instance, microarray approaches can be applied to determine the presence or absence of genes from a particular region of the subseafloor using comparative genomic hybridizations or to examine gene expression profiles.

Novel culturing methods include those that rely on dilution to extinction in very-low-nutrient media that have been used to obtain bacterial isolates from oligotrophic freshwater (e.g., Crater Lake, Oregon) and marine (e.g., the Sargasso Sea; Rappé et al., 2002) systems and are adaptable to use in studies of subseafloor life. A critical need in environmental microbiology is to elucidate the ecological roles of the most abundant habitat-specific phylogenetic clades. Therefore, cultivation of representative organisms from dominant phylogenetic clades is an important step in initiating additional studies linking diversity with function. Cultured microorganisms are also excellent targets for whole genome sequencing and comparative analyses to aid the creation and data mining efforts of metagenomic and post-metagenomic approaches as well as studies of population genetics.

Activity—IODP can provide access to many biogeochemical regimes within the subseafloor from which a polyphasic approach that incorporates geochemical and molecular techniques should be used to characterize microbial metabolic activities. By extending current shipboard protocols, geochemical analyses of cored sediments can determine concentrations of key terminal electron acceptors (e.g., NO_{3-}, Fe(III), Mn(IV), H_2, CO_2, SO_4^{2+}) and electron donors (CH_4, Fe(II), H_2S, low molecular weight fatty acids), as well as additional soluble geochemical constituents (isotopic ratios). These data can then serve as guides to specific metabolic processes within the sediment (D'Hondt et al., 2002, 2004; Parkes et al., 2005; Hinrichs et al., 2006) and basalt (Cowen et al., 2003). Molecular assays that target domain level and lineage specific fractions of the population using SSU rRNA genes (DNA-based) and SSU rRNA (RNA-based) can identify the structure of total communities (Inagaki et al., 2006) and metabolically active communities (Sørensen and Teske, 2006), respectively (Fig. 3). Fluorescent *in situ* hybridization assays that target SSU rRNA molecules within active microbial cells can detect and quantify subsurface microbial populations (Schippers et al., 2005; Biddle et al., 2006). The abundance of functional genes and quantification of enzymes (hydrogenase, phosphatase) can then be utilized to determine the relative activity of specific metabolic pathways that may contribute to local geochemistry. Stable isotope probing (SIP) can also be incorporated to identify carbon utilization, addressing a number of questions including the contribution of heterotrophic versus autotrophic communities within the subsurface. Specific metabolic pathways previously identified within IODP core sediments can therefore be characterized using these and other molecular techniques to identify the lineages responsible for these pathways and begin to address unresolved issues, including but not limited to spatial heterogeneity, isolation of subseafloor communities, and horizontal gene flow.

A majority of this microbiological work would be accomplished postcruise. However, efforts will be made to develop and refine new shipboard and *in situ* technologies. The outcome of both geochemical and molecular measurements will provide a better understanding of the interaction of microbes and their biogeochemical environment, build better biogeochemical models in the oceans, and link surface life and the contribution of subseafloor life to global carbon and other biogeochemical cycles.

Dispersal and Evolution of Subseafloor Life

Exploration of subseafloor life offers an unmatched opportunity to explore the fundamental processes and mechanisms that have determined and continue to drive the evolution and dispersal of life on Earth.

The fundamental processes that influence the geographic distribution of all life include evolutionary processes that shape the diversity of microbial assemblages through their effects on the growth and death of individuals and populations; dispersal processes that serve to isolate or connect microbial assemblages; and environmental factors that favor winners and losers among the microbes present in a given environment.

Almost nothing is known about how these processes and their consequences play out in the subsurface world. The extent to which subseafloor life is an archive for organisms from the surface world, or a source of genomic, evolutionary, and ecological innovation for the surface world, can be debated. Do evolutionary pressures and mechanisms of microbial dispersal operate differently in the subseafloor communities than in surface communities? Is subseafloor diversity a subset of the diversity in the upper world, or have subseafloor processes of organismal dispersal and environmental selection led to identifiable endemic assemblages? Have novel groups of organisms evolved to take advantage of energy sources that are not commonly considered important in the surface world, such as radiolysis of water, serpentinization reactions, and other subsurface energy sources? Is there selection for or against major metabolic and life history strategies, e.g., metabolic specialization versus a generalism? Can one identify signatures of surface life in subseafloor microbial assemblages, and conversely, can one find evidence that subseafloor life is exported to the surface world?

Geosphere-Biosphere Interactions

Interactions between the deep subseafloor ecosystem and the geosphere occur on scales from very local to global. These interactions may ultimately affect climate, evolution of the global biosphere, and structure and function of the

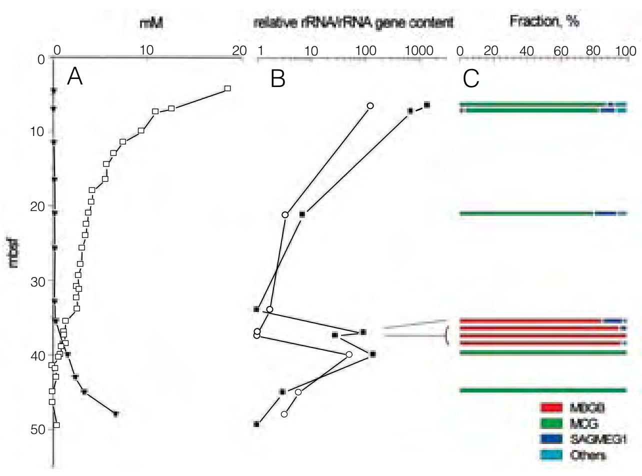

Figure 3. Population structure of uncultured deep subsurface archaea and rRNA concentration in geochemically distinct sediment horizons of ODP Site 1227 (Sørensen and Teske, 2006). [A] Concentration profile of sulfate (squares) and methane (triangles) at Site 1227. [B] Relative amount of rRNA (black squares). A value of 1 corresponds to the detection limit. The data are compared with the amount of archaeal DNA in each sample quantified by Q-PCR (circles, redrawn from Schippers et al., 2005). [C] Phylogenetic composition of clone libraries from each depth. The sample from 37.75 mbsf was extracted twice and amplified using two primer sets, yielding 3 independent clone libraries. MBG-B: Marine benthic group B, MCG: Miscellaneous Crenarchaeotal Group, SAGMEG-1: South African Gold Mine Euryarchaeotal group 1. These archaeal lineages are shown in red in the subsurface phylogeny in Fig. 2.

lithosphere. Scientific drilling can address the question of how subseafloor microbial processes and products are related to processes and properties of the overlying surface world (the ocean and the atmosphere). These include, but are not limited to 1) the global balance of oxidants and reductants, 2) the acid-base system of the world ocean, 3) primary productivity uncoupled from the photosynthetic surface world, 4) physical and chemical alteration of deep sediment, and 5) crustal geologic structure.

Scientific drilling of continental margins has demonstrated that massive levels of methane exist along continental margins and may principally be derived from the deep subseafloor biosphere (Fig. 4). Paleoclimatic studies suggest that this energy-rich compound enters the overlying ocean water and the atmosphere and dramatically alters climate. Rates of methanogenesis in deep marine sediments along continental margins are poorly constrained, and recent evidence strongly implicates the important role of microbes in the production of higher hydrocarbons such as ethane and propane (Hinrichs et al., 2006). Another climate driver includes the production and consumption of nutrient compounds. For example, we have no clear idea of the biological fixation, removal, and/or production of nitrogen in deep subseafloor environments. Profiles of dissolved and solid phase N compounds suggest that these compounds are being cycled in deep subseafloor sediment. The acid-base system of the deep ocean is also subject to deep subseafloor processes. Subseafloor metabolism produces and consumes alkalinity and may have a significant effect on ocean pH and thus climate. Understanding the overall effect of the subseafloor biosphere on the oceanic acid/base balance (and climate) requires quantification of the net rates of metabolic redox reactions and the factors that control these rates. The redox state of buried carbon and its modification with burial and age as it enters subduction zones have clear implications for global carbon and redox budgets. Exchange of oxidants and reductants between the mantle, crust, and ocean may be significantly altered by deep subsurface processes (Hayes and Waldbauer, 2006). These are all global aspects of coupling of the geosphere and deep subseafloor processes that cause us to ask: what would life in the surface biosphere look like if the deep subsurface biosphere did not exist?

There are numerous potential mechanisms for connecting material and energy flow between deep geosphere processes and life in deep subseafloor environments. On Earth's surface, sunlight overwhelmingly provides the energy for primary productivity; in the subsurface however, the nature of primary productivity is not yet constrained. For example, processes that sustain subsurface primary productivity may be potentially more diverse than those that sustain surface primary productivity, and they may ultimately feed into the ocean-climate system. Because of the high likelihood for abiotic production of hydrogen and simple organic compounds, places where water interacts with ultramafic rock are obvious drilling targets. This type of interaction takes place in a variety of tectonic settings, including rifted continental margins, lava-starved mid-ocean ridge segments, and suprasubduction zone forearcs. The lithosphere community (e.g., 21st Mohole Mission) has a large interest in exploring geodynamic and petrogenetic aspects of these settings. Radiolysis of water may provide a cryptic source of energy for primary production in colder subseafloor environments (Jørgensen and D'Hondt, 2006).

Moreover, the impact of deep sub-surface processes on lithologic properties in crustal and sedimentary environments is largely unknown. Key properties of porosity, permeability, surface area, and the viscosity of interstitial fluids may be significantly altered by sub-surface life processes.

To appreciate the extent and importance of geosphere-biosphere interactions in the deep subseafloor, scientific ocean drilling must focus on (1) understanding the processes, pathways, and products of interaction between microbial activity in the subseafloor and the ocean/atmosphere system; (2) elucidating the magnitude and rates of these processes and their ability to influence the environment and climate of the ocean/atmosphere system; and (3) determining the evolution of these interactions over geological time.

Expeditionary Strategies

The IODP provides a unique facility for studying deep subseafloor life. No other organization provides direct access to deep subsurface environments throughout the world ocean. Nowhere else has a comparable sampling capability been developed. Microbiological samples need to be evaluated for contamination by seawater or drilling fluid, as a single cell or DNA molecule might cause erroneous results, and IODP offers essential contamination assessment unlike any other scientific operation. IODP offers a controlled framework for sample handling, archiving, and analysis in microbiology, biogeochemistry, and related disciplines that allows for data integration and cross-sample comparisons. A large set of chemical and physical metadata generated on board is easily integrated into biological experiments. Furthermore, the program provides sites appropriate for long-term *in situ* experiments on and in the subseafloor, on a broad range of spatial and temporal scales.

Multiple expeditionary strategies will be necessary to explore subseafloor life and habitats. These include (1) single expeditions dedicated to specific subseafloor life objectives; (2) incorporation of dedicated holes or sites into legs scheduled for other purposes (e.g., through an Ancillary Program Letter); (3) participation as a shipboard or shore-based scientist on expeditions scheduled for other purposes; (4) routine measurements and routine archiving of appropriate samples on many or all IODP expeditions; and (5) in special cases, such as required by installation of subseafloor microbial observatories, multi-expedition (multi-platform) projects. In every case, including routine legacy sampling, consideration of microbiological sampling should be an integral part of expedition planning.

Technology Recommendations

The Ocean Drilling Program (ODP) and the IODP have built a solid framework for occasional study of subseafloor life; however, a number of issues must be addressed to improve studies of deep subseafloor microbial communities and to render such studies routine. The primary objective is to assure that, whenever and wherever possible, coring and sampling handling will facilitate characterization of subseafloor life.

Core recovery (quality and quantity): Coring technology should be optimized to increase quality and, when possible, to increase quantity of material. Advances from industry and from ODP experiments can be leveraged to achieve this goal. Approaches to minimize drilling disturbance and fluid circulation include alteration of existing drilling practices (e.g., use of mud motor, "drilling over" to extend use of hydraulic piston corers to great depth); monitoring activity at the drill bit (to improve quality); bit/shoe redesign; and alteration(s) of core barrel and liners. These changes will greatly enhance the microbiological and biogeochemical value of cored material. For example, they will provide samples of crucial niches at geologic interfaces (e.g., lithologic contacts and fractured materials), and they will improve the rigor and quality of downstream analyses.

Figure 4. Methane hydrate (white patches) in freshly drilled, organic-rich, methane-supersaturated deep subsurface sediment (Peru Trench, ODP Site 1230, 5086 m water depth, 96 m below seafloor).

Diagnostic monitoring of core quality: Quality control issues have been previously addressed with methods to quantify the intrusion of drilling fluid (Smith et al., 2000; House et al., 2003; Lever et al., 2006). Contamination is particularly problematic with igneous samples, and this issue needs to be carefully addressed.

Use of Contamination Tracers—Quantitative contamination tracing should be done on all cores to be used for microbiological study. Existing tracers for monitoring and quantifying contamination [a perfluorocarbon tracer (PFT) and fluorescent beads] have been key components of recent advances in study of subsurface life (Smith et al., 2000; House et al., 2003; Lever et al., 2006), but contamination tracing can and should be greatly improved. Detection limits should be enhanced by further improvement of techniques and by use of a chemical tracer less volatile than the current PFT. Other categories of tracers (e.g., quantum dots) and tools (e.g., 3-D imaging techniques) should be considered to enhance the quality, rigor, and simplicity of analyses. A standardized nucleic acid based method should be developed for monitoring cross-contamination during drilling. The geochemistry and microbiology programs should be directly coupled to monitor gases and contamination tracers.

Onboard handling protocol—Microbiological samples should be aseptically handled and, when appropriate, anaerobically maintained. An appropriate temperature-controlled handling method should be established. Rigorous monitoring of reagents should be conducted.

Personnel—A dedicated, full-time microbiologically trained technician is essential for diagnostic monitoring, archival sampling, and routine measurements. In addition, one or more microbiologists and one or more biogeochemists are needed to maximize scientific return on all cruises.

Maintenance of in situ *conditions*: As study of subsurface life grows within IODP, the program will need to consider methods for maintaining *in situ* conditions during coring and sample handling. Many analyses are compromised by depressurization and uncontrolled temperature fluctuations during core retrieval and handling. Core processing should be optimized to minimize changes in temperature, e.g., by recovering cores as quickly as possible and sampling them in a temperature-stabilized environment. IODP should also explore methods for insulating the core after removal from the core barrel.

To date, all ocean drilling microbiological samples have undergone depressurization prior to subsampling. Development of sub-sampling tools, or experimental chambers, that can be mated to the pressure coring systems and used to acquire samples or to initiate experiments, is possible. Sensors can be adapted into the design of pressure core barrels to provide time series measurements of important parameters. There may be opportunities for microbiologically relevant spectral measurements using sapphire windows built into the barrels or by changing barrel composition (e.g., aluminum rather than steel) to allow volumetric imaging (X-ray CT, NMR, or PET) for microbial subsampling. However, microbiologists and biogeochemists must identify specific needs and objectives for these experiments before engineering design can be successfully integrated with science requirements.

Sample collection and archiving: Routine collection and preservation of microbiological samples and routine measurements of biological parameters have not been a component of drilling operations. We recommend that a routine sampling program be implemented on all legs and on all three drilling platforms. Microbiological sampling requires specific procedures for core handling that is best accomplished by a dedicated hole.

As an initial step toward this routine program, we recommend an experiment in integrating biodiversity sampling, archiving, and measurements as part of every drilling leg. The development of this database will establish baseline information that could be screened for parameters of interest by individual investigators (porewater chemistry, ocean basin, subseafloor depth, cell density variation, etc.), who could then request samples for the investigator's analysis of choice. A two-year experiment within the IODP that includes a well advertised, clear and straightforward sample request plan is recommended, with the following guidelines.

Requirements for sample handling and sample storage depend on the downstream analyses (see below). The following considerations are pertinent to samples that will be used for shipboard analyses and those that will be shipped to shore-based laboratories or repositories for postcruise studies. Although it is anticipated that most samples will be collected from anaerobic environments, low productivity and/or low carbon environments may be oxygenated, and thus samples should be stored appropriately. In all cases, avoidance and quantification of sample contamination with non-indigenous microbes during drilling and sample handling is of paramount importance.

<u>Biomarker samples</u>—Frozen samples are used for analyzes of nucleic acids, lipid biomarkers, amino acids, etc. These analyses are the central component of biodiversity studies. These samples should be collected as soon as possible and immediately frozen in liquid nitrogen or a -80°C freezer to ensure the safe delivery of samples from the sampling site to the repositories. Samples stored in ultra-low temperature freezers can be maintained in an anaerobic environment by adapting the method of Cragg et al. (1992).

<u>Samples for cultures and activity experiments</u>—Samples that will be used for culture-based isolations and microbial activity measurements should be stored at 4°C until analyzed. Samples that are to be used for microbial culturing must be protected from temperature and/or oxygen fluctuations (e. g., samples from an anaerobic environment should be maintained under anaerobic conditions). Samples for anoxic culturing work should be transferred to gas-tight trilaminate bags containing an oxygen scrubber.

<u>Microscopy samples</u>—Samples used for microscopy (e.g., direct cell counts, FISH, microautoradiography) are fixed with aldehydes such as formaldehyde or glutaraldehyde, washed with ethanol:PBS (1:1) solution, and stored at -20°C. For FISH-based sample storage it is recommended that samples be preserved according to established protocols (Pernthaler et al., 2002). For these samples, the particular assay dictates the details necessary in the fixation process.

<u>Sample shipping</u>—Because maintaining proper temperature for each category of analysis is essential, samples must be shipped under appropriate temperature conditions (e.g., frozen samples should be shipped in dry ice, and culturing samples should be shipped under 4°C refrigeration). A temperature logger should be included in each microbiological or biogeochemical shipping container to provide the thermal history of the samples during transit.

<u>Sample archiving</u>—IODP should establish a repository for routinely collected samples that are collected and stored for subsequent microbiological analysis. The subsamples should be collected as soon as possible after removal from the core in sterile syringes and stored appropriately as described below. This legacy sample should be taken from the middle of the core in near proximity to samples taken for biogeochemical, contamination tracing, and other microbiological analyses.

<u>Standardization of sample-handling protocols</u>—An IODP laboratory protocol book is suggested to help in standardizing procedures and techniques for microbiological sampling, shipping and archiving. This book can be made available electronically on the IODP web site.

Routine Microbiological Measurements: The openly accessible DSDP/ODP/IODP database of routine measurements is a tremendous strength of the scientific drilling program. This allows for continued analysis of the data whether it is using new techniques or global syntheses of data (Parkes et al., 2000; D'Hondt et al., 2002). Therefore, it is necessary to institute routine measurements that can be realistically obtained during IODP drilling projects and which provide useful data to assist in the study of subsurface microbiology. All of these data should be made available to the shipboard party via the standard IODP database.

Metabolic products and reactants—Concentrations of some electron acceptors (e.g., dissolved SO_4^{2-}) and some electron donors (e.g., CH_4) are already measured routinely as part of the shipboard geochemistry program, which should be expanded to include a much larger range of metabolites. These include, for example, dissolved iron and dissolved manganese in anoxic formation water, and dissolved oxygen and nitrate in the upper sediment column of all sites and above the sediment/basalt interface at open-ocean sites.

Biomass—Biomass quantification should be instituted as a routine measurement.

Total cell counts. Counting of total microbial cells is essential for quantifying subsurface biomass. Each legacy sample for cell counts should be divided in half, with one half counted on ship, and the other preserved and placed at -20°C for comparative counts or more specific quantification on shore. While most ODP/IODP cell counts have been generated using acridine orange direct counts (Cragg et al., 1990), we recommend phasing in the use of a nucleic acid stain with lower background and more stable fluorescence (e.g., SYBR Green) for cell enumeration (Lunau et al., 2005 for sediment analysis; Santelli et al., 2006 for basalt). Total cell counts tend to result in maximum estimates of biomass; however, the detection limit can be reduced by orders of magnitude by separating the cells from the sediment prior to enumeration (Kallmeyer et al., 2006). To standardize cell counts, we suggest that IODP consider adding a flow cytometry instrument to the shipboard laboratory.

As soon as possible, additional methods for assessing biomass should be compared by study of subsamples from multiple sites and cores. Candidate methods include:

(a) Phospholipids. Intact phospholipids can be used to estimate the total microbial biomass and broad community composition in sediment samples (White et al., 1979; Zink et al., 2003). This can be achieved with an HPLC-MS system by quantitative and qualitative analysis of the intact polar membrane lipids, which are diagnostic of live cells (Sturt et al., 2004; Biddle et al., 2006).

(b) ATP. Quantification to estimate active biomass has been used successfully in cores (Egeberg, 2000).

People qualified to undertake these techniques are rare. Members of the IODP community should work to build a pool of expertise sufficient to undertake one or more of these assays during or immediately after most expeditions.

Community composition—Further information on microbial populations can be gathered by using microscopic techniques such as FISH, CARD-FISH, CTC, and live/dead staining, which distinguish different phylogenetic groups and distinguish between active cells and dead or inactive cells. Samples can also be monitored for viruses.

Standardization of laboratory protocols—An IODP handbook is recommended to describe standard microbiological procedures (routine surface decontamination prior to sample handling, biological waste decontamination, etc). The Explanatory Notes from ODP Expedition 201 may serve as a guide for what may be achieved with such a handbook (D'Hondt et al., 2003). As with the suggested microbiology sampling handbook, this book can be made available electronically on the IODP web site.

Technology transfer and data dissemination: Because microbiologists generate some types of samples and data that are unique to their field, some additional issues need to be addressed.

Sequence data—Sequencing of nucleic acids has become the accepted standard method for identifying microorganisms. The usefulness of the data resides in the ability to compare sequences. This is accomplished by submission of sequences to internationally recognized, publicly accessible databases.

Molecular biology offers a suite of tools that provide a powerful strategy for gaining new insights into the diversity of microbial life of the subseafloor. This strategy is particularly powerful when complemented with culture-based methods. The coordinated structure of IODP offers a unique opportunity to explore microbial life in the subseafloor using these integrated approaches. To maximize this opportunity requires capture of genetic data (including sequences of 16S rRNA and 18S rRNA genes) from samples collected throughout the program and to make the genetic data available to a wider scientific audience. For this approach to succeed, the provenance of all the genetic information must be catalogued and integrated with the metadata obtained by other IODP efforts (e.g., lithology, geochemistry) in a relational database. To best complete this task, we recommend that the IODP consider building a relational database suitable to the data types collected in this program, as well as exploring interfacing with other repositories of genetic and metadata where feasible and appropriate. Examples of these databases include GenBank, the Ribosomal Database Project (RDP), and CAMERA.

Culture isolates—A common goal for many microbiologists is to obtain pure cultures of microorganisms to perform detailed studies on their physiological capabilities, produce specific enzymes or metabolic byproducts, and so on. It is common practice to place subsamples of the cultures in publicly accessible culture collections. In keeping with the open, international cooperation established during the previous decades of scientific ocean drilling, IODP should require that cultures of microorganisms isolated from cores be deposited in a publicly accessible culture collection (Takai et al., 2005). As the program grows and more microbial cultures become available, we recommend that a deep subseafloor culture collection be established. A good example and possible leverage would be to consider a repository in the U.S. Department of Energy's Subsurface Microbial Culture Collection (SMCC).

Microbiological Observatories: In situ experimentation is ultimately the best mechanism for determining *in situ* processes, including microbial colonization, mineral-microbe interactions and effects of tectonic/volcanic events on subseafloor communities. It is necessary to conduct time-series and manipulative experiments to constrain the roles, if any, that microorganisms may play in rock alteration and secondary mineral formation. The power of *in situ* experimentation for studying colonization and mineral alteration has been demonstrated at the seafloor (Edwards et al., 2003, 2004; Edwards, 2004) and in terrestrial systems (Bennett et al., 1996; Edwards et al., 1998; Hiebert and Bennett, 1992). Subseafloor microbiological experiments are now being conducted for the first time as part of the Juan de Fuca hydrogeology experiments made possible by IODP Leg 301 (Fisher et al., 2005; Nakagawa et al., 2006). Similar experiments are proposed for some subsurface life proposals active in the IODP system. Support for CORK operations and technology is imperative for the success of such projects. This includes necessary support for existing technologies, such as the CORK hardware and associated sensors (pressure, temperature, strain and tilt sensors) and samplers (OSMO). Additional *in situ* capabilities will be necessary to meet future microbiology needs. These needs include samplers and incubators for microbiological analyses, fluid transfer systems, pumping and power systems for seafloor sampling from bore holes, and *in situ* sensors for key metabolic species, such as hydrogen and methane. Study of active hydrothermal systems will require development of high temperature sampling and technology for *in situ* measurements. These developments must be supported and encouraged by IODP and governmental funding agencies in IODP countries.

Inclusion of microbiological observatories in IODP proposals requires early identification of critical design specifications. Experimental modules that could be deployed in boreholes will require iterative design efforts by scientists and engineers.

Partnership with Other Organizations

Study of subseafloor life may provide significant opportunities to partner with industry and government agencies. For example, the U.S. Department of Energy is interested in advanced drilling technology for sampling in high-temperature/high-pressure environments. Such partnerships may require alignment of interests and new models for IODP collaboration and funding. Existing industry tools—such as the modular dynamic (formation) tester (MDT) with a flow control module for fluid sampling across the borehole wall with quality assurance methodology to reduce contamination—may greatly facilitate downhole integration of microbiological and formation fluid sampling. The challenge will be to find ways to deploy these tools in IODP boreholes and work out economic models for their deployment. IODP applications of existing tools may require alternative methods of tool deployment (e.g., wireline reentry, ROV guidance of tools into boreholes, or use of larger-diameter drill pipe) to make the desired measurements.

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Scientific Drilling in a Central Italian Volcanic District

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Introduction and Goals

The Colli Albani Volcanic District, located 15 km SE of Rome (Fig. 1), is part of the Roman Magmatic Province, a belt of potassic to ultra-potassic volcanic districts that developed along the Tyrrhenian Sea margin since Middle Pleistocene time (Conticelli and Peccerillo, 1992; Marra et al., 2004; Giordano et al., 2006 and references therein). Eruption centers are aligned along NW-SE oriented major extensional structures guiding the dislocation of Meso-Cenozoic siliceous-carbonate sedimentary successions at the rear of the Apennine belt. Volcanic districts developed in structural sectors with most favorable conditions for magma uprise. In particular, the Colli Albani volcanism is located in a N-S shear zone where it intersects the extensional NW- and NE-trending fault systems. In the last decade, geochronological measurements allowed for reconstructions of the eruptive history and led to the classification as "dormant" volcano. The volcanic history may be roughly subdivided into three main phases marked by different eruptive mechanisms and magma volumes. The early Tuscolano-Artemisio Phase (ca. 561–351 ky), the most explosive and voluminous one, is characterized by five large pyroclastic flow-forming eruptions. After a ~40-ky-long dormancy, a lesser energetic phase of activity took place (Faete Phase; ca. 308–250 ky), which started with peripheral effusive eruptions coupled with subordinate hydromagmatic activity. A new ~50-ky-long dormancy preceded the start of the late hydromagmatic phase (ca. 200–36 ky), which was dominated by pyroclastic-surge eruptions, with formation of several monogenetic or multiple maars and/or tuff rings.

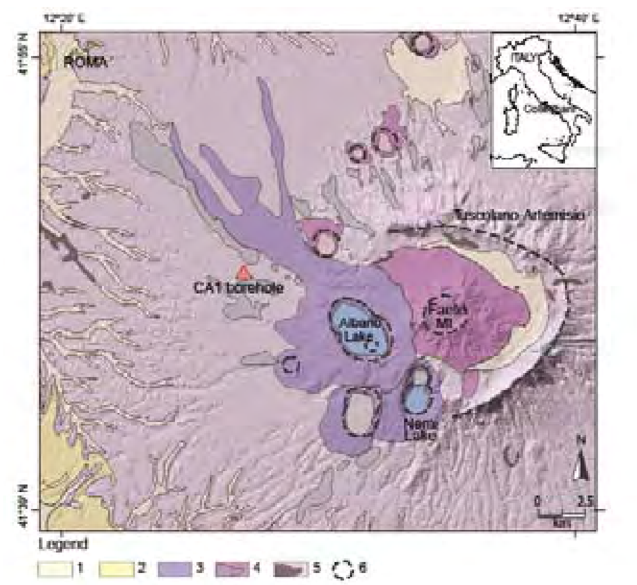

Figure 1. Geological map of Colli Albani area and CA1 borehole location. Color legend: 1) Holocene alluvial deposits; 2) Plio-Quaternary sedimentary deposits; 3) “Hydromagmatic phase” (200-36 ky); 4) Deposits of “Faete phase” and related lava flows (308–250 ky); 5) “Tuscolano Artemisio phase” and related lava flows (561–351 ky); 6) Crater rims; (modified after Marra et al., 2004).

Periodic unrest episodes have been directly observed in the area of most recent volcanism, posing a threat not only to this densely populated area but also to the nearby city of Rome (Amato and Chiarabba, 1995; Chiarabba et al., 1997; Pizzino et al., 2002). Unrest activities include i) intermittent seismic swarms of shallow depth and small-moderate magnitude earthquakes, ii) episodes of CO_2, radon, and H_2S emissions, and iii) pulses of surface uplift. In the framework of two multidisciplinary projects (DPC and FIRB, see details below), the Colli Albani 1 borehole (CA1, 350 m) was drilled to directly investigate the volcano at depth (Mariucci et al., 2007).

In this project, detailed analyses of borehole data will be coupled to geological, geophysical, and geochemical studies. The main goals are to better characterize the shallow crust structure beneath the volcanic complex, to define the present-day stress field, and to understand the formation and emanation of hazardous gases. Finally, a seismometer will be installed at depth in order to acquire outstanding seismological records without anthropogenic noise.

Drilling and On-site Measurements

The borehole is on public land about 10 km south of Rome close to Santa Maria delle Mole village, adjacent to the west rim of the Tuscolano-Artemisio caldera. Considering the high gas concentrations in the aquifers (mainly CO_2 and H_2S), which have caused illness and casualties among habitants and animals, a blowout preventer was installed at the wellhead. Moreover, for safety reasons H_2S concentrations and combustible gases were constantly monitored.

Drilling was conducted in one stage during April and May 2006 by an Italian company (SO.RI.GE. srl) using a Casagrande C8 machine and wire-line technique. A vertical borehole and continuous coring down to 350 m were planned to sample volcanic and sedimentary sequences. Wire-line coring allowed for a very good core recovery (about 99%) that enabled reconstruction of the detailed stratigraphy of the volcanic units down to the Plio-Pleistocene sedimentary basement. From top to bottom the borehole stratigraphy consists of the typical volcanic succession pertaining to the Tuscolano-Artemisio Phase of activity, spanning the interval 561–351 ky and a Plio-Pleistocene sedimentary sequence characterized by ~150 meters of consolidated clays underlying a ~20-m-thick sand layer followed by sand at the hole bottom (the last ~5 m).

Figure 2. Blowout event.

The borehole was drilled with standard rotary technique down to 25.5 m, followed by wire-line diamond coring with downscaling diameters (178 mm for the first 18 m, 152 mm up to 25.5 m, 122.7 mm up to 204 m, all with 85 mm core; 96.1 mm from 204 m to 300 m, with 63.5 mm cores and 75.6 mm up to 350 m, with cores of 47.6 mm). Each 3-m-long core section was cut in pieces of 1-m length and packed in wooden boxes, now curated at Istituto Nazionale di Geofisica e Vulcanologia (INGV)-Rome. Some quick geotechnical analyses were performed on site, such as the Schmidt Hammer and the Barton Comb, to compute the joint compressive strength (JCS) and the joint roughness coefficient (JRC), respectively. A quick analysis of fractures and faults was also performed on the cores in the field.

Three hydraulic fracturing tests had been planned between 320 m and 350 m for a first evaluation of the local stress field in the area, in particular to better constrain the minimum horizontal stress. Unfortunately, a blow-out occurred (Fig. 2) during the positioning of the hydraulic fracturing probe in the well, causing a collapse of the deepest part of the borehole. Overpressured fluids (mainly in the form of gases) leaked out of the well for about one hour with a wellhead pressure of ~30 bar, sputtering up to about 5 m above ground level for one day with pressure stabilizing around 15 bar. This phenomenon, probably caused by the presence of a sandy unit at 345–350 m, allowed collecting fluid samples for quick geochemical analyses on-site and in the laboratory. Fluids are an aqueous mixture of CO_2, H_2S, helium, aromatic hydrocarbons, and other gases. Although hampering some geophysical investigations, this blow-out gave direct access to the deepest fluids ever sampled in the area up to now. After fluid samples were collected, the flux was stopped by pumping water into the borehole and restoring the initial conditions.

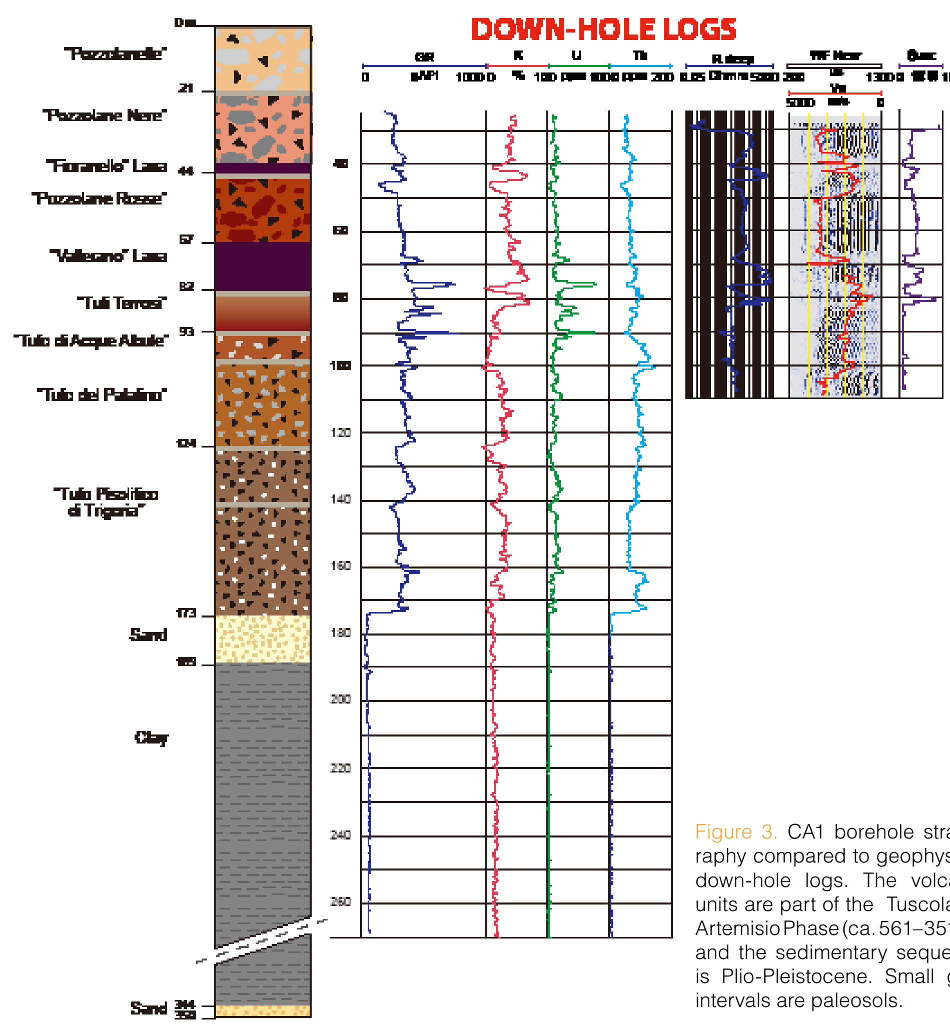

Figure 3. CA1 borehole stratigraphy compared to geophysical down-hole logs. The volcanic units are part of the Tuscolano-Artemisio Phase (ca. 561–351 ky) and the sedimentary sequence is Plio-Pleistocene. Small gray intervals are paleosols.

In order to evaluate the *in situ* physical properties of volcanic rocks and to estimate the state of stress, the following geophysical logs were performed using the International Continental Scientific Drilling Program (ICDP) - Operational Support Group (OSG) slim-hole probes: spectrum gamma ray, sonic, magnetic susceptibility, electric resistivity (dual-laterolog), four-arm dipmeter, and borehole televiewer. Spectral gamma logs were recorded down to 270 m, whereas other tools were only deployed down to 110 m as a consequence of the blow-out (Fig. 3).

The borehole was cased down to 200 m and plugged with cement in the lower part hosting a broad-band seismometer. Now it serves as a seismic station for the Italian national centralized seismic network managed by INGV.

Ongoing Research

Some data analyses and laboratory measurements on samples are still ongoing. We analyzed downhole logs and compared them to the detailed stratigraphy obtained from cores, defining the main physical characters of the main volcanic units. Moreover, selected samples were taken on the most representative volcanic units to determine physical properties such as elastic wave velocities under different pressure conditions. Breakout analyses from both caliper and televiewer data are performed to get the horizontal minimum stress direction and to analyze fractures from televiewer images. All cores from the logged interval were scanned using an optical DMT Core Scanner at GeoForschungsZentrum in Potsdam (Germany) for digital documentation and structural analysis. A lot of fault planes with striae along the sedimentary cores were recognized, and these will be analyzed using an innovative high resolution thermal field emission scanning electron microscope to highlight some characteristics of the microstructures. Ar-Ar dating will be applied to define the age of a drilled lava flow that is poorly known so far, and mineralogical and geochemical analyses will unravel the characteristics of the volcanic units. Biostratigraphic analysis of nannoplankton and foraminifera and detailed measurements of magnetic susceptibility of Pliocene clays will allow us to define the depositional environment and former positions of shorelines. Dynamic tests on the clays will provide data useful to define the local seismic response of the consolidated clays that form the basement of the volcanic sequence below the City of Rome. Measurements of natural gamma radiation on the cores will be compared with downhole measurements. The goal is to integrate core data with new geodetic and seismological data for physical and numerical modeling to understand the behavior of the whole volcanic complex.

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The Second Deep Ice Coring Project at Dome Fuji, Antarctica

by Hideaki Motoyama

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Introduction

Throughout the history of the polar icecaps, dust and aerosols have been transported through the atmosphere to the poles, to be preserved within the annually freezing ice of the growing ice shields. Therefore, the Antarctic ice sheet is a “time capsule" for environmental data, containing information of ancient periods of Earth’s history. To unravel this history and decode cycles in glaciations and global change is among the major goals of the Dome Fuji Ice Coring Project.

With an elevation of 3810 m, Dome Fuji (39˚42’E, 77˚19’S) is the second highest dome summit on the Antarctic ice sheet and might be one of the locations holding the oldest ice in Antarctica. The base of the ice underneath Dome Fuji is estimated to have formed at the beginning of the glacial cycle in the Quaternary era. Analysis of this ice can shed light on the mechanism of Quaternary glacial cycles. The second deep ice coring project at Dome Fuji, Antarctica reached a depth of 3028.52 m (3810 m above sea level) during the austral summer season in 2005/2006 (Figs. 1 and 2). The recovered ice cores contain records of global environmental changes going back about 720,000 years. During the recent 2006/2007 season the Japanese Antarctic Research Expedition (JARE) team finally reached a depth of 3035.22 m at the Dome Fuji station on 26 January 2007.

Figure 1. Dome Fuji station and other deep ice coring sites on Antarctica ice sheet. The routes to and from Dome Fuji station are shown by the green, red, and blue arrows.

Figure 2. Dome Fuji station in January 2006.

First Deep Ice Core Drilling at Dome Fuji

In December 1996, during the first deep ice core drilling campaign at Dome Fuji, the 37th JARE team had succeeded coring the ice to a depth of 2503 m. Due to a shortage of antifreeze supply, the drilling team temporarily stopped drilling and waited to receive supplies to arrive with the next drilling team (JARE 38). However, while reaming and chip recovery were repeated using the ice core drill in order to keep the hole open, the drill became stuck at the end of December at a depth of approximately 2300 m. The subsequent 39th and 40th JARE teams attempted to recover the drill by injecting high density liquid (hydrochlorofluorocarbon) 200 m below the surface of the ice sheet (100 m below the liquid level), but this attempt failed, and the borehole had to be abandoned.

A second deep ice coring project was commenced at Dome Fuji during 2001. It was decided to draw on new drilling technology developments and to establish a new borehole about 43 m north of the abandoned one with the aim of full penetration to bedrock. A pilot hole was drilled to a depth of 122 m, and a casing was installed by the 42nd JARE wintering team in 2001. In 2002 the 43rd JARE team constructed a new deep ice core drilling house, updated the station equipment, and began repairing the logistic equipment. The 44th Dome Fuji wintering team completed and prepared the new deep ice core drilling system in 2003—a completely new deep ice core drill of 4.0 m core barrel length. It subsequently proved to be of true world class quality, when it was able to recover 3.84 m of the ice core in each operation with almost no unexpected difficulties caused by ice chip clogging. Due to logistical considerations, only summer operations were performed.

Deep Ice Core Drilling Technology

The deep ice coring drill used during this project is an electro-mechanical liquid-filled type. A schematic diagram and photos are shown in Fig. 3, and the main specifications of the drills used at Dome Fuji are summarized in Table 1. The ice drill consists of a core barrel, a chip chamber, a pressure tight section, and an anti-torque section (Takahashi et al., 2001). Three cutters are attached to cut an ice core of 94 mm diameter, leaving a borehole of 135 mm diameter. To prevent borehole closure during drilling, the borehole is filled with an anti-freezing fluid, n-butyl acetate. Its density is about equal to the ice, and the viscosity at temperatures below −50˚C is low. Since the second deep ice coring project drilled only during the austral summer season, the design of the drill could be improved to increase the productivity under this premise. The equipment was able to penetrate up to 3.84 m for each core, as opposed to the 2.3 m cored during the first deep ice coring project. Effective transportation and storage of the cutting chips generated by the drill turned out to be one of the biggest problems. Technicians experimented with various pumps to solve this problem, and finally an archimedean screw pump was used, which is operated by rotating a core barrel (Fig. 3C) through a spiral spring located within a double tube. A propeller-like booster attached to the driving shaft of the core barrel provides momentum for the transportation of the borehole liquid and cutting chips to a chip chamber (Fig. 3B).

A special pipe perforated with many small holes was manufactured for storing the cutting chips, while the liquid could easily pass through the perforations (Fig. 3A). However, the cutting chips create a countercurrent in the chip chamber during drill ascent, leading to leakage of the chips from the chip chamber. A current prevention system, including a new check valve and direct current (DC) drill motor, was adopted to prevent this from happening.

Difficulties and Progress

In the first season, 2003/2004, the final drilling depth achieved was 362 m despite significant logistics problems with weather and transportation of equipment. However, with the considerable experience gained in the 2003/2004 season, it was possible to drill ice cores smoothly during the summer season of 2004/2005. The hole was deepened by approximately 1500 m, reaching a total drilling depth of 1850.35 m.

To reach the bedrock of Antarctica under the ice sheet, 1200 meters had to be drilled in the last projected summer season 2005/2006. Hence, it was necessary to arrive at the Dome Fuji station at the earliest possibility. The team arrived at the station on 17 November 2005. The drilling resulted in a record high 133 m of drill core per week without encountering problems, and a drilling depth of 3000 m was achieved on 12 January 2006. Through most drilling runs, a 3.7-m ice core of excellent quality was obtained. When the drilling depth exceeded 3000 m near the bedrock, the ice temperature was close to the pressure melting point. The cutting chips immediately froze to become ice, which made chip transportation within the corer very difficult. At this depth, nearly four hours were required for each single ice coring operation, with performance rapidly decreasing. Finally, only ten centimeters of the ice core could be drilled on average with each core. Because it had been expected that the "warm" ice would cause problems, the normal drill was replaced with a special short teflon-coated drill in an attempt to determine the most suitable drilling method. The final drilling depth was 3028.52 m on 23 January 2006, when drilling had to stop to provide sufficient time for demobilization of the operation and crew.

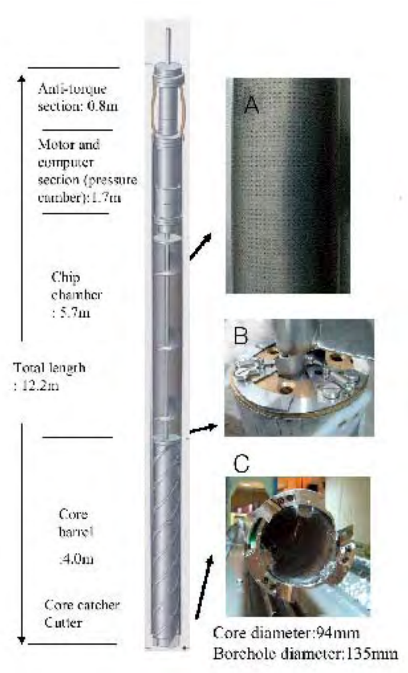

Figure 3. Schematic of a new JARE deep ice coring drill. [A] Chip chamber with many small holes for stable cutting; [B] Adverse current prevention system of chips when the drill is raised; [C] Development of special alloy for cutter which can be used to core cold hard ice as well as "warm" softer ice.

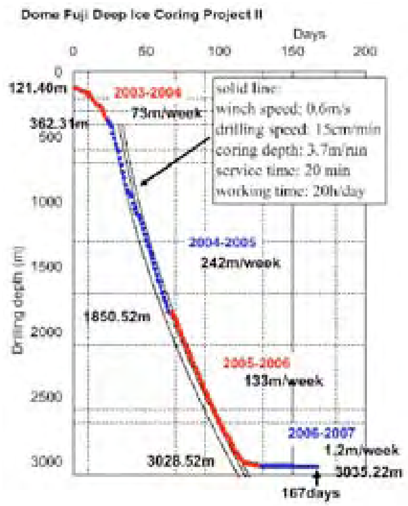

Figure 4. Progress of Dome Fuji Deep Ice Coring Project.

Ultimately, to reach the bedrock, the deep ice core drilling was extended for another year. In the fourth drilling season, 2006/2007, the total drilling period was 39 days. The total drilling length was 6.70 m, and the final drilling depth reached was 3035.22 m. The average core length was approximately 10 cm, which was half the length expected. The overall progress of deep ice core drilling throughout the seasons 2003 to 2007 is summarized in Fig. 4.

When a drilling depth of 3034.34 m was reached, a special type of small ice pieces appeared to be abundant in the chip chamber and in the frozen water chip accumulating on the

Table 1: Specs of the JARE phase 1 drill and the improved model used for normal and "warm" ice during Phase 2.

Item	Phase 1 Model	Phase 2 Model	Phase 2 Model (for warm ice)
Type	Electro-Mechanical Drill	Same as Phase 1	no change
Core ØxL	94 mm x **2,200 mm**	94 mm x **3,840 mm**	94 mm x **2,000 mm**
Cutting Speed	15-20 cm/min	Same as Phase 1	no change
Static Pressure	30MPa	Same as Phase 1	no change
Drill Size ØxL	122 mm x **8,593 mm**	122 mm x **12,200 mm**	122 mm x **8,106 mm**
Cutter	3 x Block Type	Same as Phase 1	**Special**
Core Barrel ØxL	101.6 mm x **2,321 mm**	101.6 mm x **4,000 mm**	101.6 mm x **2,256 mm**
Chip Chamber ØxL & Density	112 mm x **3,260 mm** ρ = **500 kg m^{-3}**	112 mm x **5,533 mm** ρ = **550 kg m^{-3}** **Hole: 1.2 mm Ø x 45,000**	112 mm x **3,160 mm** ρ = **550 kg m^{-3}** **Hole: 1.2 mm Ø**
Chip Pump	Archimedean Pump & 1 Turn Screw Booster	Archimedean Pump & 1 or 0.75 Turn Screw Booster x 2-3	Archimedean Pump & 1 or 0.75 Turn Screw Booster x 2
Motor Output Power	**AC Brushless Motor 600 W for 15 min at 12,000 rpm**	**DC Permanent Magnet Motor with Brushes, 600W for 15 min. at 4,000 rpm.**	no change
Reduction Gear Type & Ratio	**4 Stage Planetart Gear 1/170**	**Harmonic Drive Type: CSF17, 1/100, 1/80 (, 1/50)**	no change
Electronics	Monitoring Computer (10 Parameters)	Same as Phase 1 (version 2)	no change
Pressure Chamber ØxL & Pressure	122 mm x 1,700 mm 30 MPa	Same as Phase 1	no change
Anti-Torque	3 x Leaf Spring	Same as Phase 1	no change
Cable ØxL	7-H-314K, 7.72 mm x 3,500m	Same as Phase 1	no change
Hole Liquid	n- butyl acetate	Same as Phase 1	no change
Special Items		**1. System to Prevent Adverse Current of Chips** **2. Super Banger**	**1. Special Cutter Mount** **2. Teflon Coated Drive Shaft, Screw Booster, Cutter, Core Catcher, Outer Tube, Core Barrel**

ice core (Fig. 5). The crystal structure of these strange ice pieces differed from that of the cutting ice chips. The conclusion was that water beneath the ice sheet had probably leaked into the borehole and had frozen in the drill. In addition, the ice core was found to be contaminated with small rocks. Hence, since liquid water existed near the bedrock, the drilling machine was covered with ice when it was positioned in the ground to drill through the ice sheet, which had a temperature of –55°C or lower. The shape of the ice underneath the drill resembled frozen drops of water. Drilling was carefully continued for the next days, and finally, the last ice core was recovered topped with mysterious white frozen water from a depth of 3035.22 m below the surface.

Preliminary Analysis of the Ice Core

The oxygen isotope ratio of the ice core was measured to determine its age. This ratio fluctuates depending on the paleotemperatures, and it can be used to study the past glacial-interglacial cycles in great detail. The ages of the ice cores were estimated by comparing the determined age with the Dome C ice core data from the European Project for Ice Coring in Antarctica (EPICA). As a result, the deepest ice cores at Dome Fuji were estimated to be approximately 720,000 years old. Traces of atmospheric gases were trapped as air bubbles in the ice sheet and will be analyzed.

The ice cores recovered from the Dome Fuji station confirmed that the history of global environmental changes could be continuously recorded from 720,000 years in the past. More analysis will be conducted to clarify the Earth's climate, microorganisms present in ice, and space climate. Currently, ice core studies are being conducted in cooperation with the National Institute of Polar Research in Tokyo, Japan, other universities, and other institutes.

For more information about the Dome Fuji Deep Ice Coring Project see the Web link below.

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Related Web Link

http://polaris.nipr.ac.jp/~domef/home/eng/index-e.html

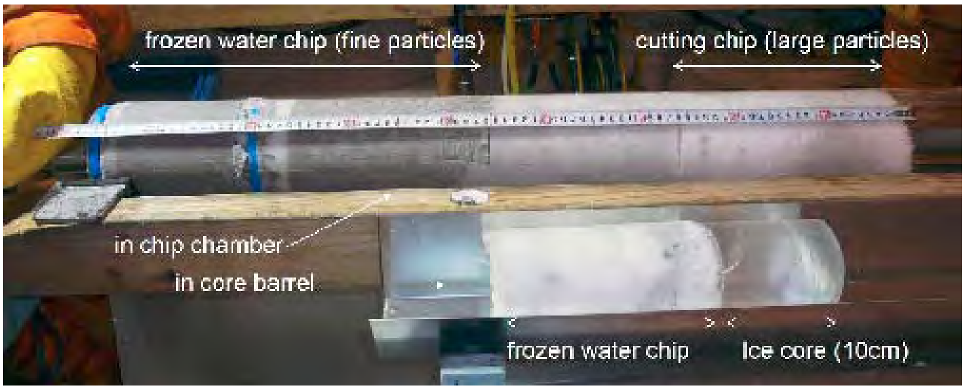

Figure 5. Cutting chips of ice core and a lot of frozen water chips.

Tenaghi Philippon (Greece) Revisited: Drilling a Continuous Lower-Latitude Terrestrial Climate Archive of the Last 250,000 Years

by Jörg Pross, Polychronis Tzedakis, Gerhard Schmiedl, Kimon Christanis, Henry Hooghiemstra, Ulrich C. Müller, Ulrich Kotthoff, Stavros Kalaitzidis, and Alice Milner

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Introduction and Goals

With the dramatically increasing manifestation of anthropogenic forcing on the Earth's climate, understanding the mechanisms and effects of abrupt climate change is crucial to extend the lead time for mitigation and adaptation. In this context, the climate variability during the Quaternary represents the closest analogy to present-day climate change. Unprecedented insights into both short-term (i.e., decadal-to centennial-scale) and long-term (i.e., orbital-scale) climate variability over the last 740 kyr have been derived from ice cores from polar regions (Dansgaard et al., 1993; EPICA community members, 2004). These records show that the higher latitudes repeatedly witnessed temperature changes of more than 10°C within human time scales (Severinghaus et al., 1998). Considerably less information is available on the characteristics of abrupt climate change in the middle and lower latitudes and on their imprint on terrestrial environments. These regions are, however, home to the majority of the Earth’s population, and consequently they will witness the greatest impact of future climate change on people's lives.

Located in a strategic position between the higher-latitude (i.e., North Atlantic Oscillation-influenced) and lower-latitude (i.e., monsoonally-influenced) climate systems, the Mediterranean region is particularly sensitive in recording abrupt climate change and its imprint on terrestrial ecosystems. Moreover, terrestrial climate archives from the Mediterranean borderlands yield rich, diverse biotic signals also during colder intervals because the region’s climate was relatively mild even under fully glacial boundary conditions. In contrast to higher-latitude records, this warrants the detailed analysis of short-term climate variability in terrestrial environments throughout the full range of climatic boundary conditions of the Quaternary.

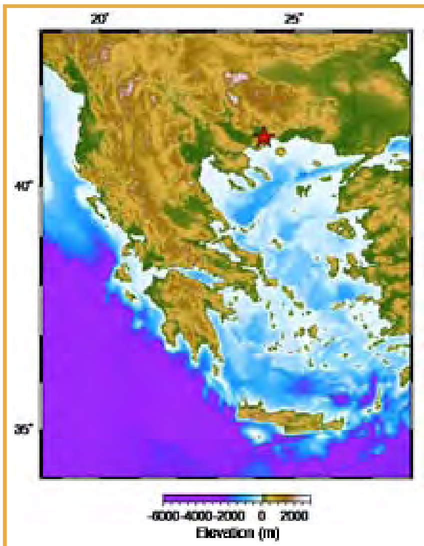

Figure 1. Map of the Aegean region with location of the Tenaghi Philippon drill site (red star).

In light of the above, the climate archive of Tenaghi Philippon (site within the Drama Basin, Eastern Macedonia, Greece; Fig. 1) plays an exceptional role. Since the initiation of pollen-based vegetation analyses from drill cores in the late 1960s (Wijmstra, 1969), it has been increasingly recognized as one of the best terrestrial archives of Quaternary climate history in Europe. This prominent position is due to (1) its temporal length, spanning the last 1.35 million years and comprising at least nineteen consecutive glacial-interglacial cycles (Tzedakis et al., 2006); (2) its completeness, as evidenced by the close climato-stratigraphical correspondence with global deep-sea records; and (3) its proximal position with regard to glacial refugia of thermophilous plants in SE Europe, which reduces the time lag between atmospheric forcing and vegetation response as documented in pollen data.

Because previous investigations of the Tenaghi Philippon climate archive were restricted to a temporal resolution within the Milankovitch time band, and the core material used in these investigations has deteriorated, the potential of this site for the analysis of abrupt climate change has remained virtually untapped. Therefore, a campaign has been initiated to re-drill this archive; it is funded by the German Research Foundation, the Wilhelm Schuler Foundation, and the Royal Society (U.K.). The aim of this initiative is an interdisciplinary analysis of short-term climate variability under interglacial, “semi-glacial”, and glacial boundary conditions of the Quaternary. Given the close proximity of the Tenaghi Philippon site to the Aegean Sea, special emphasis is placed on the identification of short-term environmental perturbations during intervals coeval with sapropel formation in the Eastern Mediterranean Sea. Disciplines include palynology, sedimentology, stable isotope geochemistry, coal petrology, photogrammetric and magnetic susceptibility core logging, magnetostratigraphy, and radiometric (^{14}C, $^{40}Ar/^{39}Ar$) dating.

Drilling at Tenaghi Philippon

The Philippi peatland, which includes the Tenaghi Philippon site, is situated in the intramontane Drama Basin, Eastern Macedonia, Greece (Fig. 1). Owing to rapid subsidence that may have started in Late Miocene times, the

Drama Basin constituted a limnic to telmatic setting throughout the Middle and Late Quaternary. Much of the basin fill that accumulated during this time consists of peat, resulting in the largest peat and lignite deposit of SE Europe. Based on the results of previous scientific drilling during the late 1960s to mid-1970s, the sedimentary succession at Tenaghi Philippon is known to comprise peat, mud, lake marls, and clays until 198 m depth; further downhole, and until the maximum depth drilled (280 m), clastic input increases such that sediments are palynologically non-productive (Wijmstra and Smit, 1976a, b; Van der Wiel and Wijmstra, 1987).

A 60-m-long core from Tenaghi Philippon (40°58.40'N, 24°13.42'E; 40 m above sea level) was drilled over three weeks in April 2005 using a WIRTH Eco1 drilling rig (Fig. 2) and a special, non-rotating probe driven by a pneumatic hammer system ("Dystel hammer"). The core, which has excellent recovery (97.8%), is now stored in the core repository of the Institute of Geosciences, University of Tübingen, Germany. Magnetic susceptibility measurements were performed on the entire core. After splitting the core into an archive half and a working half, it was photogrammetrically scanned and lithologically described. To facilitate non-destructive magnetostratigraphic measurements (e.g., to identify the Blake and Lachamps reverse-polarity events), core segments that may comprise these events according to the preliminary age model (see below) have been left intact.

Figure 2. Drilling rig WIRTH Eco1 used for drilling in the Drama Basin. The Phalakron mountain range (2232 m a.s.l.), which borders the Drama Basin to the northeast, is visible in the background.

Initial Results

A first, preliminary age model for the entire core has been established based on the analysis of pollen samples from the bottom of each 1-m-long core segment. The overview record presented in Fig. 3 indicates a succession of pollen zones reflecting open, steppe-like vegetation intercalated with zones reflecting the prevalence of Mediterranean forests (Fig. 4). Figure 3 also shows a preliminary correlation with the SPECMAP chronology (Imbrie et al., 1984) and insolation values (Berger and Loutre, 1991). We interpret the interval from 0 m to 5 m to represent the Holocene and Late Glacial, with Late Glacial climate fluctuations being yet unresolved because of low resolution. The interval from 5 m to 19 m is approximately correlative to Marine Isotope Stages (MIS) 2 to 4. The intervals from 19 m to 34 m and 34 m to 42 m represent MIS 5 and MIS 6, respectively. The stratigraphic interpretation below 42 m is less straightforward due to the low-resolution age model available at present. According to our current interpretation, the interval from 42 m to 57 m correlates with MIS 7, and the interval down-core corresponds to MIS 8. Although absolute age control is not yet available, our data indicate that the core comprises at least the last 250 kyr, potentially even the last 290 kyr.

Tephra layers in the core, which have the potential for $^{40}Ar/^{39}Ar$ dating, provide a unique opportunity for age control independent from both palyno-stratigraphic and radiocarbon dating. Moreover, they allow the direct correlation with other terrestrial and marine climate archives from the Eastern Mediterranean region. As depicted in Fig. 3, the magnetic susceptibility curve exhibits prominent spikes that point to the positions of tephra layers. The inspection of layers with high magnetic susceptibility within the already split part of the core resulted in the identification of tephra layers with glass and pumice shards. The layer at 7.59 m represents the PhT2 tephra derived from the Cape Riva eruption of Santorini at ~22 kyr BP and correlates with Y-2 in the Mediterranean Sea. The PhT3 tephra at 12.80 m is

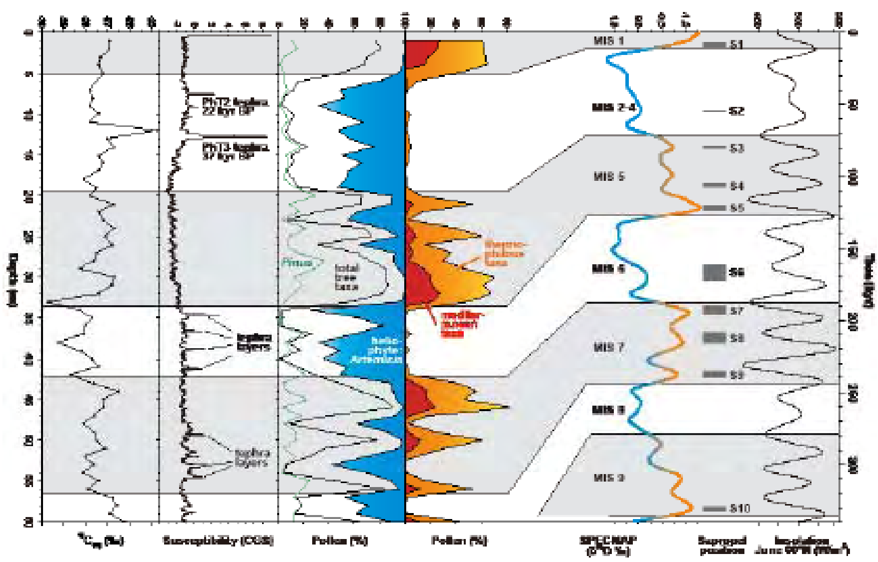

Figure 3. First results from the new core, comprising palynological, magnetic susceptibility and carbon isotope data. The tentative correlation of the pollen data with the SPECMAP chronology (Imbrie et al., 1984) and insolation values (Berger and Loutre, 1991) suggests that the record comprises at least the last 250 kyr. The magnetic susceptibility curve shows positions of PhT2 and PhT3 tephra layers and also indicates positions of older tephra layers.

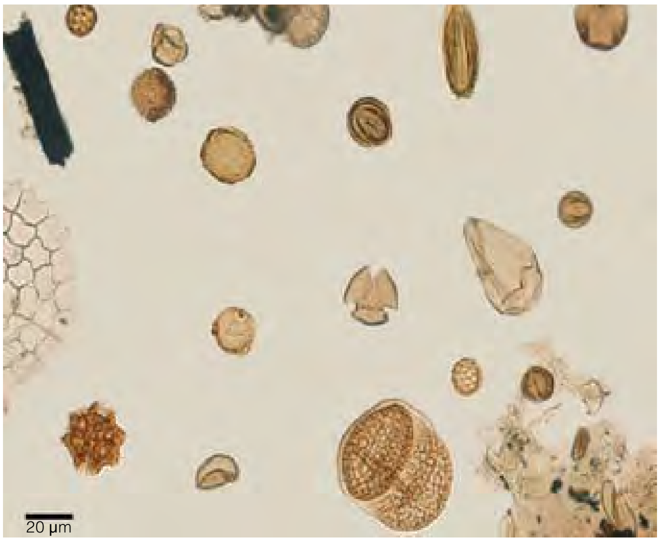

Figure 4. Typical glacial pollen spectrum from the new core (Sample is from a core depth of 10.0 m, corresponding to Marine Isotope Stage 3).

correlative to the Campanian Ignimbrite and Y-5 in the Mediterranean Sea, having a $^{40}Ar/^{39}Ar$ age of ~37 kyr BP (S. Wulf, 2006, pers. comm.).

High resolution studies of the core are currently underway, including palynology and sedimentology (Frankfurt, Leeds), stable isotope geochemistry, radiocarbon and tephra dating (Frankfurt), and coal petrology (Patras). The analytical phase of this multi-disciplinary project is scheduled for the next three years. Following the compilation of data by each group/discipline, a synthesis study is planned for the final phase of the project. The integration of the resulting data will allow new insights into the characteristics of abrupt (decadal- to centennial-scale) climatic change and their consequences for terrestrial environments in the Mediterranean region.

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Fig. 1. Bathymetry and elevation taken from the GEBCO digital atlas (IOC, IHO, and BODC, 2003).

Fig. 2. Photo by Ulrich C. Müller.

Fig. 4. Photo by Ulrich Kotthoff.

Directional Drilling and Stimulation of a Deep Sedimentary Geothermal Reservoir

by Ernst Huenges, Inga Moeck, and the Geothermal Project Group

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Introduction

Strata of Lower Permian sandstones and volcanics are widespread throughout Central Europe, forming deeply buried (on average, 4000-m) aquifers in the North German Basin with formation temperatures of up to 150°C. Stimulation methods to increase their permeability by enhancing or creating secondary porosity and flow paths are investigated by deep drilling. The goal is to map the potential for the generation of geothermal electricity from such deep sedimentary reservoirs using a doublet of boreholes—one to produce deep natural hot water and the other to re-inject the water after use. For these purposes, an *in situ* downhole laboratory was established in Gross Schönebeck, north of Berlin, Germany (Fig. 1).

At present, two 4.3-km-deep boreholes have been drilled. The first well (GrSk 3/90), originally completed in 1990 as a gas exploration well abandoned due to non-productivity, was reopened in 2000 and hydraulically stimulated in several treatments between 2002 and 2005. In 2006, the second well (GrSk 4/05), planned for extraction of thermal waters, was drilled to form a doublet system of hydraulically connected boreholes. In this second well the Lower Permian sandstones and the underlying volcanic rock are targeted for stimulation by hydrofracturing. The resulting reservoir should have an increased productivity with a minimal requirement for auxiliary energy to drive the thermal water loop (reservoir-surface-reservoir) and with minimal risk of a temperature short circuit of the system during the planned 30-year utilization period. The current experiment is designed to demonstrate sustainable hot water production from the reservoir between the two wells.

Background

Increasing demands for renewable energy are leading to utilization of geothermal resources from areas with typical (low) continental thermal gradients, as found in western and central Europe. For the exploitation of such low-enthalpy reservoirs, it is necessary to enhance the geothermal system. Two basic technologies based on hydraulic fracturing of the reservoir by variations in fluid pressure (Economides and Nolte, 1989; Huenges and Kohl, 2007) can be applied:

- creation of an artificial heat exchanger at depth and using surface water for heat extraction from mostly dry rocks, e.g., Soultz-sous-Forêts (Baumgärtner et al., 2004)
- creation of artificial pathways at depth to enhance the water flow from water-bearing reservoir rocks, e.g., Gross Schönebeck (Huenges et al., 2004).

Lower Permian strata comprising upward fining siliciclastic rocks underlain by volcanic rocks (Fig. 1) are well-known from extensive gas exploration and production in NE Germany. Suitable framing for the study includes (1) formation temperatures above 120°C, in rocks at >3000 m depths, (2) large and regional extent of representative reservoir rocks, and (3) a variety of lithologies available for investigation. An abandoned gas exploration well (GrSk 3/90) at Gross Schönebeck completely meets these requirements and gives access to hot, water-bearing Lower Permian successions. It was therefore selected from a suite of existing wells, reopened in December 2000, and deepened from 4264 m to 4309 m to serve as a geothermal *in situ* laboratory.

Hydraulic Stimulation

Nine months after the well was reopened, a re-equilibrated temperature of 149°C was measured at 4285 m depth. The formation pressure was determined from long-term pressure

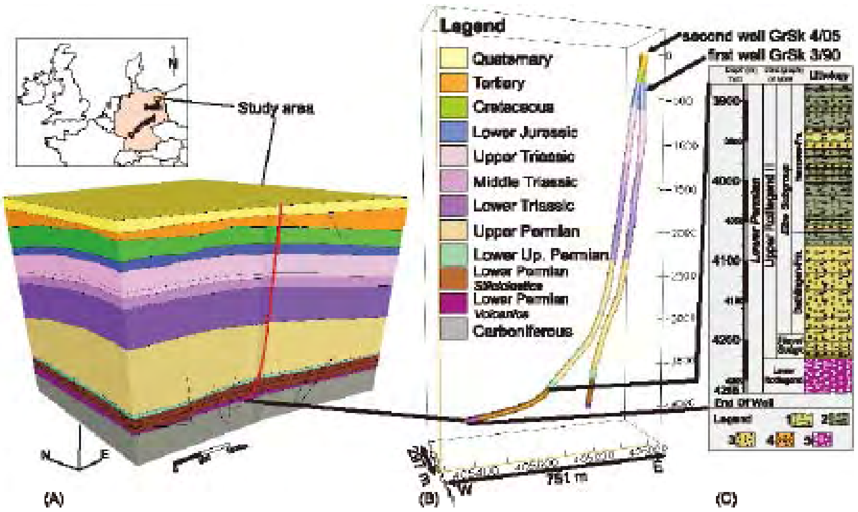

Figure 1. Location of the drilled doublet system and the geothermal aquifer in the Lower Permian of the northeast German Basin. [A] 3-D model showing the geological environment of the Gross Schönebeck field. [B] Configuration of the geothermal doublet system. [C] Lithology of the Lower Permian along the recently drilled new well. Legend: 1-claystone, 2-siltstone, 3-fine to middle grained sandstone, 4-middle to coarse grained sandstone, 5-andesitic volcanic rock (modified from Moeck et al., 2007).

logs showing equilibrium conditions close to 44.9 ± 0.3 MPa at 4220 m depth. A series of stimulation experiments was performed. First, open hole hydraulic gel-proppant fracturing treatments were conducted in two pre-selected sedimentary reservoir zones in the Lower Permian sandstones at a depth of ~4 km. The main inflow zones could clearly be identified. In a second step, massive water fracturing treatments were applied over the entire open hole interval from 3874 m to 4309 m depth. Pressure response analyses and well logs indicated the creation of vertical fractures and a bilinear flow regime in the reservoir, implying that an enhanced geothermal system suitable for geothermal power production had formed (Zimmermann et al., 2005; Huenges et al., 2006).

Directional Drilling of a Second Well

Hydraulic-thermal modeling based on data from the first well, along with regional structural analyses, identified the best possible well path geometry for the second well (Zimmermann et al., 2007). The borehole was designed parallel to the minimum horizontal stress direction and perpendicular to potentially hydraulic fractures to decrease auxiliary energy requirements for the thermal water loop in the planned doublet. Furthermore, this setup provides a low risk of a temperature short circuit of the system within the projected thirty years of utilization. Due to infrastructural requirements, the new well (GrSk 4/05) was located at the same drill site as GrSk 3/90 (27 m distance) but with a bottom hole some 500 m apart due to the reservoir requirements. Therefore, the new drilling operations required (1) a large hole diameter due to the deep static water table of the reservoir and the respective withdrawal during production (housing for the submersible pump), (2) directional drilling to intersect the target horizon at the derived offset from the existing hole and to increase the inflow conditions through well inclination in addition to later multiple fracturing, and (3) a special drilling mud concept to avoid formation damage of the reservoir as much as possible.

Initially, the large hole diameter (23") drilling experienced difficulties in clay-dominated sections requiring pumping capabilities beyond 4000 L min^{-1}. Complete casing cementation was necessary, because thermally induced stress from hot water might have caused casing damage on the non-cemented pipes. Total fluid loss and uncontrolled hydrofracturing occurred during the bottom up cementation of the 16" crossover 13-3/8" casing, conducted with a mean slurry density of 1450 kg m^{-3}. Therefore, squeeze cementation was performed from top of the well to the former cement infiltration zone. The successful placement of the cement was controlled by thermal logging.

Following drilling of a 1600-m-thick Upper Permian evaporate section counterbalanced with a mud density of 2000 kg m^{-3}, a 9-5/8" liner was installed, which (despite a strength with a safety factor of 1.8) collapsed in the bottom region after reduction of the mud density was reduced to 1060 kg m^{-3}. Presumably, this failure was caused by additional stress components from anisotropic stress from the well inclination of ~20° in connection with the presence of highly ductile rocksalt (temperatures of 110°C in 3800 m depth). Stress concentration in interbedded anhydritic layers might have increased anisotropic stresses. The collapsed 9-5/8" liner was replaced with a combined 7" x 7-5/8" liner after sidetrakking. The latter caused further challenges, as the setting of the mechanical anchor of the whipstock required its modification for reliable operation in mud with 40% barite content. Furthermore, the borehole design needed to be adjusted due to the loss of one casing dimension. Therefore, the borehole was deepened with 5-7/8" diameter drilling into the geothermal reservoir of the Lower Permian section.

In order to avoid drilling mud which would invade the formation and reduce its permeability, the reservoir below 3900 m was drilled with a near-balanced mud density of 1030 kg m^{-3}. Borehole wall breakouts at 3940 m forced a cleaning run and an elevation of mud pressure to 1100 kg m^{-3}. This specific mud pressure was the result of a geomechanical study investigating the initiation of borehole breakouts in reservoir successions under low mud pressures (Moeck et al., 2007). Another reason for increasing the mud weight was the occurrence of H_2S below the 7-5/8" casing shoe and within the fissured lowermost Upper Permian formation. To prevent gas inflow, the mud density was partly increased up to 1200 kg m^{-3}, and a specially designed marble flour-based mud was used to minimize fluid losses into the coarse sandstone formation. Due to the danger of differential sticking and formation damage, the mud weight was lowered in subsequent drilling operations. No significant fluid losses were observed during the final drilling and casing operations.

Accessing the Geothermal Reservoir

The well reached the target along the planned borehole track (Fig. 2). A 5" liner combined with a non-cemented section of pre-perforated pipes at the bottom was installed in the lowermost section at 4400 m depth. The presence of Lower Permian middle to fine grained sandstones of the Dethlingen Formation at this depth was confirmed by cutting and well log analyses. In the well, the Lower Permian sediments reached a thickness of 340 m at the flank of structural high of the sandstones (Fig. 3). Reservoir sandstone layers with permeabilities up to 160 mD lay within the succession and have

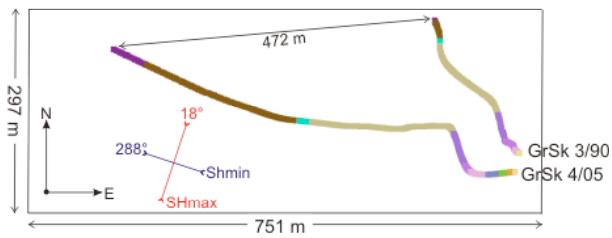

Figure 2. Top view projection of the doublet wells at Gross Schönebeck. The deviation of GrSk 4/05 is parallel to the minimum horizontal stress direction to facilitate a set of parallel hydraulic fractures.

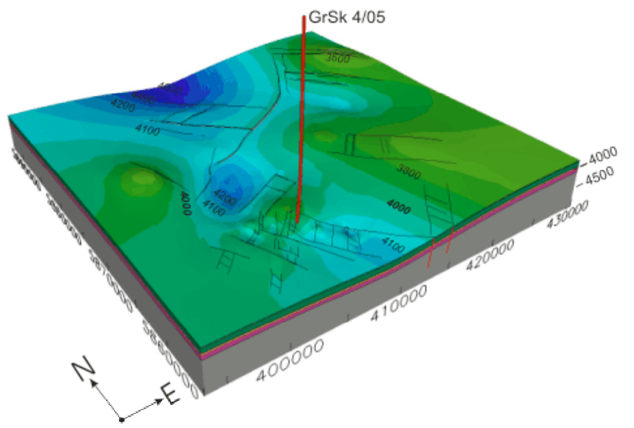

Figure 3. Structural 3-D map of the top of the reservoir rock (sandstones in the Lower Permian). The well is located at a structural high. The contour lines indicate the depth of top reservoir below sea level.

a vertical thickness of >80 m. The well inclination of 45° implies that up to 150 m of the well is within this permeable sandstone. The well deviation is oriented at 288° to optimize the hydraulic fracturing design (Fig. 2 and Holl et al., 2005). Hydrofracs are planned in the volcanic rock and some in the sandstones. Based on the previously mentioned hydraulic-thermal modeling, a distance of no less than 450 m between the bottoms of the two wells was realized to avoid a thermal breakthrough of the injected cold water directly into the production well.

Conclusions

In the Northeast German Basin, 4000-m-deep Lower Permian sandstones and volcanic rocks have been explored for geothermal energy production near Gross Schönebeck. The research strategy we applied consists of (i) re-using a former gas exploration well for logging and hydraulic stimulation campaigns, (ii) understanding the reservoir behavior based on data recovery from hydraulic treatments, (iii) optimizing the planned reservoir exploitation by analyzing the performance variances of well paths, (iv) completing the geothermal doublet system by drilling a second well, (v) future stimulating and testing the new well and installing a thermal water loop using a doublet system, and (vi) installing a binary geothermal power plant if sufficient reservoir conditions are continued. The experiences gained, especially in (iv), show that drilling a large hole diameter (23") is feasible but challenging especially in clay dominated layers; that directional drilling can be applied as a standard operation; and that a variable mud concept needs to be applied in order to react to unforeseen operational requirements such as formation damage, breakouts, or inflows. In this project, technical and scientific challenges were successfully met, and the lessons that were learned provided essential knowledge for developing future drilling strategies in deep sedimentary geothermal systems, especially in the Central European Basin System.

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http://www.gfz-potsdam.de/pb5/pb52/projects/Machbarkeit/ewelcome.html

Contribution of Borehole Digital Imagery in Core-Log-Seismic Integration

by Philippe Gaillot, Tim Brewer, Philippe Pezard, and En-Chao Yeh

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Introduction

The Integrated Ocean Drilling Program (IODP) and the International Continental Drilling Program (ICDP) use many new technologies to increase the quality of core data. A problem with drilling deep oceanic or continental crust, as well as shallow fractured rock or karstic formations, is that core recovery can be low, and much of the recovered material often consists of small, disrupted core pieces that are frequently biased toward particular types of rocks (lithologies). Even when core recovery is high (in the case of sedimentary formation), recovered cores are not always oriented; as a result, detailed structural and paleomagnetic studies are impaired.

In contrast, logging provides nearly continuous records of the *in situ* chemical and physical properties of the penetrated formation, which can be used to extrapolate the various lithologies in areas of reduced core recovery (Brewer et al., 1998).

With the advent of modern imaging tools, a fundamentally new concept has been introduced (Serra, 1989; Lovell et al., 1998). Formations are no longer scanned by a single sensors creating a single scalar log, but can be sampled multiple times horizontally and at a high rate vertically to form a dense matrix of measurements being displayed as an image. Since the mid-eighties there has been an explosive development in imaging technology, principally in terms of tools but also in terms of producing the image. The progress has been linked with the availability of downhole digitization of signals and the possibility of transmitting large data volume in real time. Where the standard logs are sampled every ~15 cm (6"), image logs may be sampled every ~0.25 cm (0.1") or less; where the standard logs have one measurement per depth point, image logs may have 360 or more.

So, digital borehole images (mm-scale) can potentially bridge the scale gap between the (dm-scale) standard logs and (µm to dm-scale) core measurements. Indeed, continuous and oriented borehole wall images provide high resolution lithologic, textural, and structural information, filling information gaps where core recovery is low and allowing orientation of cores when core recovery and undoubted features are recognized on both core and logging images. In turn, continuous and quantitative information extracted from these images can help in bridging the scale gap between log and the large scale (macroscopic, >100 m) properties of the penetrated formation. While physical principles and applications of electrical, acoustic, and optical borehole imaging tools are easily schematized in Fig. 1 (see http://publications.iodp.org/sd/05/suppl/ for details), the present paper shows some examples of quantitative analyses of electrical images that illustrate various contributions of borehole images to a fully inte-

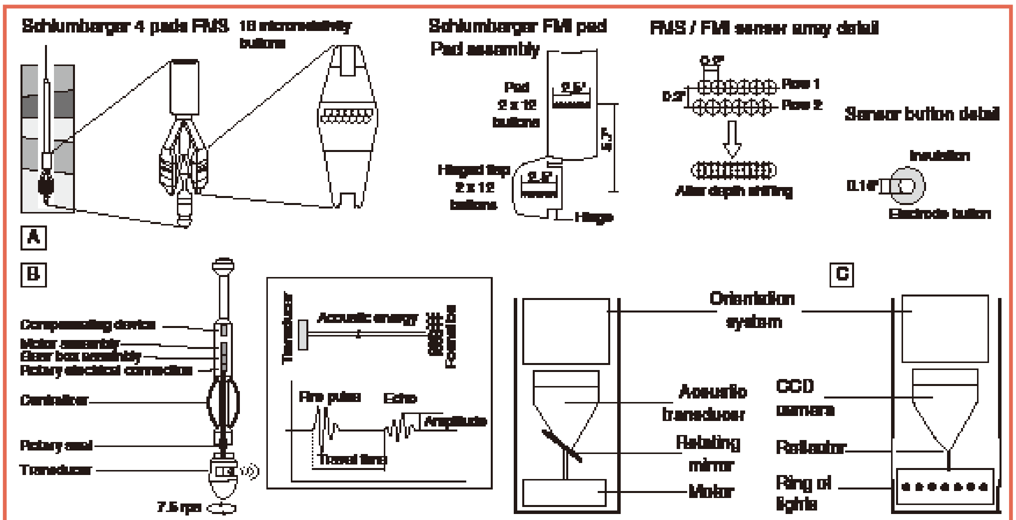

Figure 1. Sketch of electrical, acoustic and optical imaging tools. [A] Schlumberger Formation MicroScanner (FMS) with four pads, 16 buttons per pad, covering 25%–40% of hole diameter, and Schlumberger Fullbore Formation MicroImager (FMI) with 4 pads, 4 hinged flaps, and 24 buttons on each pad and flap. The hinged flap is able to increase coverage by up to 80% (modified from Ekstrom et al., 1987). The buttons are aligned in two rows; processes for depth corrections shift the recorded resistivity to one row. Each button consists of an electrode surrounded by insulation. [B] The Ultrasonic Borehole Imager features a high resolution transducer that provides acoustic images of the borehole wall. The transducer emits ultrasonic pulses at a frequency of 250 kHz or 500 kHz (low and high resolution, respectively), which are reflected by the borehole wall and then received by the same transducer. Amplitude and travel time of the reflected signal are then determined. [C] Optical televiewers generate a continuous oriented 360° image of the borehole wall unwrapped using an optical imaging system (downhole CCD camera which views a reflection of the borehole wall in a conic mirror- sketch of advanced logic technology ALT OBI40). Like electrical imaging tools and acoustic televiewers, the optical televiewers include a full orientation device consisting of a precision 3-axis magnetometer and 2 accelerometers, thus allowing for accurate borehole deviation data to be obtained during the same logging run and for accurate and precise orientation of the image.

grated core-log-seismic integration workflow.

Case Studies

<u>*Borehole images filling lithostratigraphic core gaps*</u>: Electrical borehole wall images acquired with the Schlumberger Formation MicroScanner (FMS) in Ocean Drilling Program (ODP) Hole 896A are a good example of the contribution of borehole images to reconstruct the lithostratigraphy when core recovery is low (<30%) (ODP Leg 148 Shipboard Scientific Party, 1993; Alt et al., 1996). The alternative lithostratigraphy that is constructed by combining standard scalar logging data and FMS images contains considerably more brecciated units (~30%) than suggested by the shipboard core descriptions (10%). This disparity, explained as the reflection of preferential recovery of less fractured massive flows, emphasized the necessity to fully integrate core and logging results in boreholes with reduced core recovery. In Hole 896A, different volcanic lithologies can be identified on the FMS image data by variations in electrical conductivity (Fig. 2). Massive units appear on the FMS images as extensive areas with a uniformly low conductivity and predominantly straight, branching fracture patterns (Fig. 2A). Pillow lavas show variable conductivity within a small area, but this is less variable than for brecciated units. Individual pillow lavas can often be distinguished on the FMS data owing to the curved nature of the pillow boundaries (Fig. 2B). Interstitial material usually has high conductivity. Breccias are characterized on the FMS image data by high conductivity, which is highly variable within a small area. The presence of small high-resistivity clasts can often be noted (Fig. 2C).

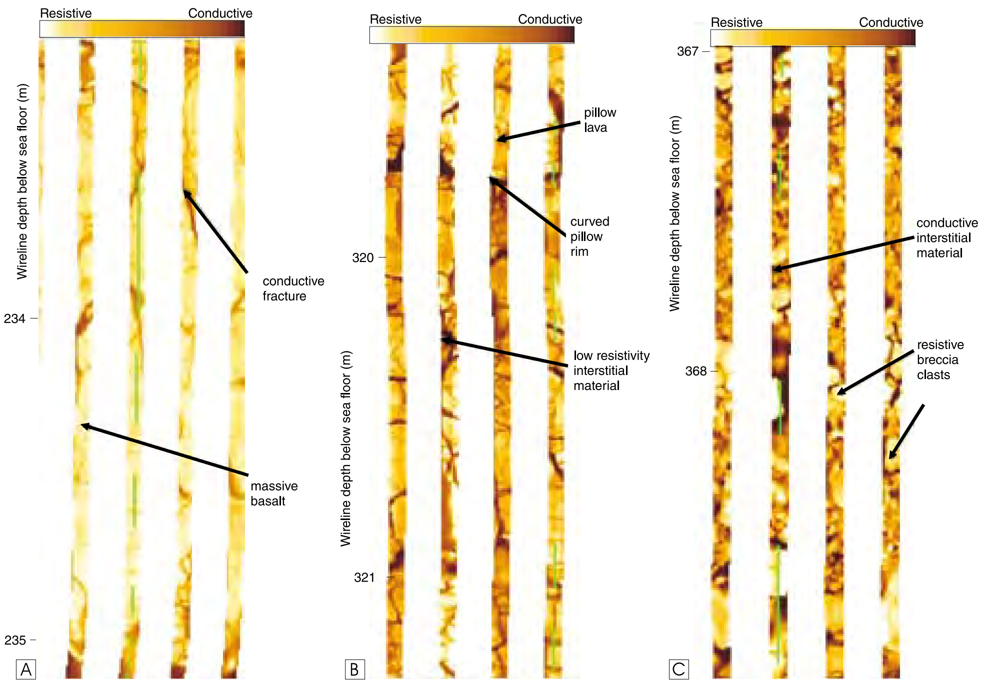

Figure 2. Formation MicroScanner (FMS) electrical images from ODP Hole 896A. [A] massive flow, [B] pillow lava, and [C] brecciated material.

<u>*Orientation of cores using borehole images*</u>: In a more general manner, although cores obtained through ocean and continental drilling provide valuable information, recovered core pieces are often initially inaccurately located and unoriented in a geographical reference frame. In these situations, logging image data are essential to supplement and enhance structural data from the recovered core. One core imaging tool used by ODP during ODP Leg 176 was a digital core scan device that produces 360° images of the outside of the core (Dick et al., 1999). These digital photographs can be unwrapped and displayed as 2-D images showing the core's entire outer surface (Fig. 3). The images can then be used to locate and measure the dip and orientation of structural features (veins, fractures, boundaries between different rock types) in the core. Assuming that the core recovery is high enough and features on core and borehole wall images are distinctive enough, such structural features on the core and logging FMS images can be matched and so allow the accurate location and orientation of individual core pieces, a key step in structural and paleomagnetic studies (MacLeod et al., 1995; Harvey and Lovell, 1998; Haggas et al., 2001). In the San Andreas Fault zone, Iturino et al (2001) used a combination Logging While Drilling (LWD) Resistivity At the Bit (RAB) image and core x-ray computed tomography images.

<u>*Formation scale information deduced from borehole images*</u>: Any paleoenvironmental reconstruction or investigation of large-scale geological bodies (through, upper oceanic crust, reservoir) requires the extension of the 1-D view of the borehole to a regional-formation scale view. The first step involves a classification of the core and downhole log responses into relatively homogeneous sub-groups (units) based on (1) a lithofacies determination relying on visual core description and measurement (core units) and (2) a visual or statistical analysis of available logging data (log units). Due to the *in situ* and continuous nature of downhole data in respect to expensive and discontinuous nature of core data, methods based on multivariate statistics of downhole log response (electro-facies-based classification; See Ravenne, 2002 for a review.) have been developed to estimate spatial distribution of heterogeneous subsurfaces (e.g., regionalized classification relying on statistical relationships between laboratory-determined hydrologic properties and field-measured geophysical properties to estimate spatial distributions of porosity, permeability, and diagenetic characteristics; Moline and Bahr, 1995). Such methods aim to predict the lithology

of the penetrated formation, but more widely attempt to provide additional formation-scale hydrologic (flow unit, reservoir permeability) or geologic (structural, environmental) information. Taking into account the increase in computational power and the higher resolution and coverage of the borehole images in respect to standard logs, such methods have been generalized to include borehole images information (e.g., texture) and have been coupled to modeling tools.

Core, borehole image, log, and formation-scale integration: Log data and digital borehole images collected from the Hole-B of the ICDP Taiwan Chelungpu-fault Drilling Project have been analyzed to establish the relationships between deformation structures and *in situ* stress, and to identify the rupture zone of the 7.6 Mw 1999 Chi-Chi earthquake. Based on standard scalar logs, three log units and five subunits are recognized as consistent with lithological units defined from visual core description (Fig. 4). Analysis of the Schlumberger Fullbore Formation MicroImager (FMI) resistivity data has also been automatically performed. This analysis, relying on the local and multi-scale properties of the wavelet transform formalism, consists in measuring the number and characteristics (size and electrical contrast) of each electric feature recorded in the high resolution logs, and so provides new high resolution "quantitative and integrative" logs—namely, the density of electrical features (Npm), the average size (wavelength, W) and average electrical contrast (C) of the detected features. In turn, combined with visual interpretation of sedimentary and structural features recognized on borehole images, these logs can be correlated to large-scale formation units and fault zones independently defined from the scalar logs and core data providing extra small-scale information on the nature of the downhole variations in natural gamma radiation (NGR), electrical resistivity, and sonic velocity (Vp) (Fig. 4).

Conclusion

Digital borehole images have the same depth coverage of scalar logs, with a resolution higher than these logs and often higher than standard core logging measurements. Relying on different physical bases, imaging tools provide a palette of high resolution, continuous, and oriented 360° views of the borehole wall from which the character, relation, and orientation of lithologic and structural planar features, as well as texture, can be defined to support detailed core analyses. Analyzed with specific methods relying on multivariate statistics or automatic extraction of quantitative attributes, these images and high resolution information derived from them allow filling the scale gap between core/sample measurements and large-scale formation properties, thus opening an avenue in addressing scientific challenges related to formation characterization.

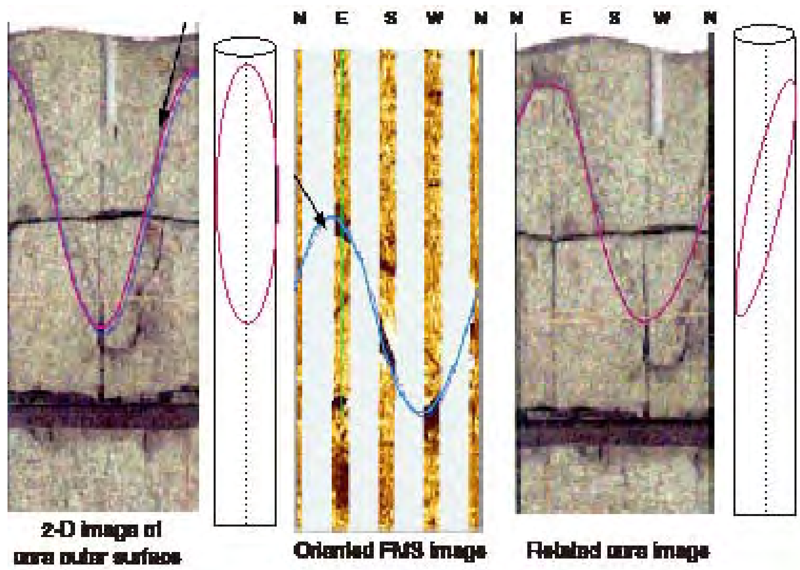

Figure 3. Reorientation of core from ODP Leg 176 using correlation with a fracture imaged by the Formation MicroScanner (FMS) electrical resistivity image tool (Modified from Haggas et al., 2001).

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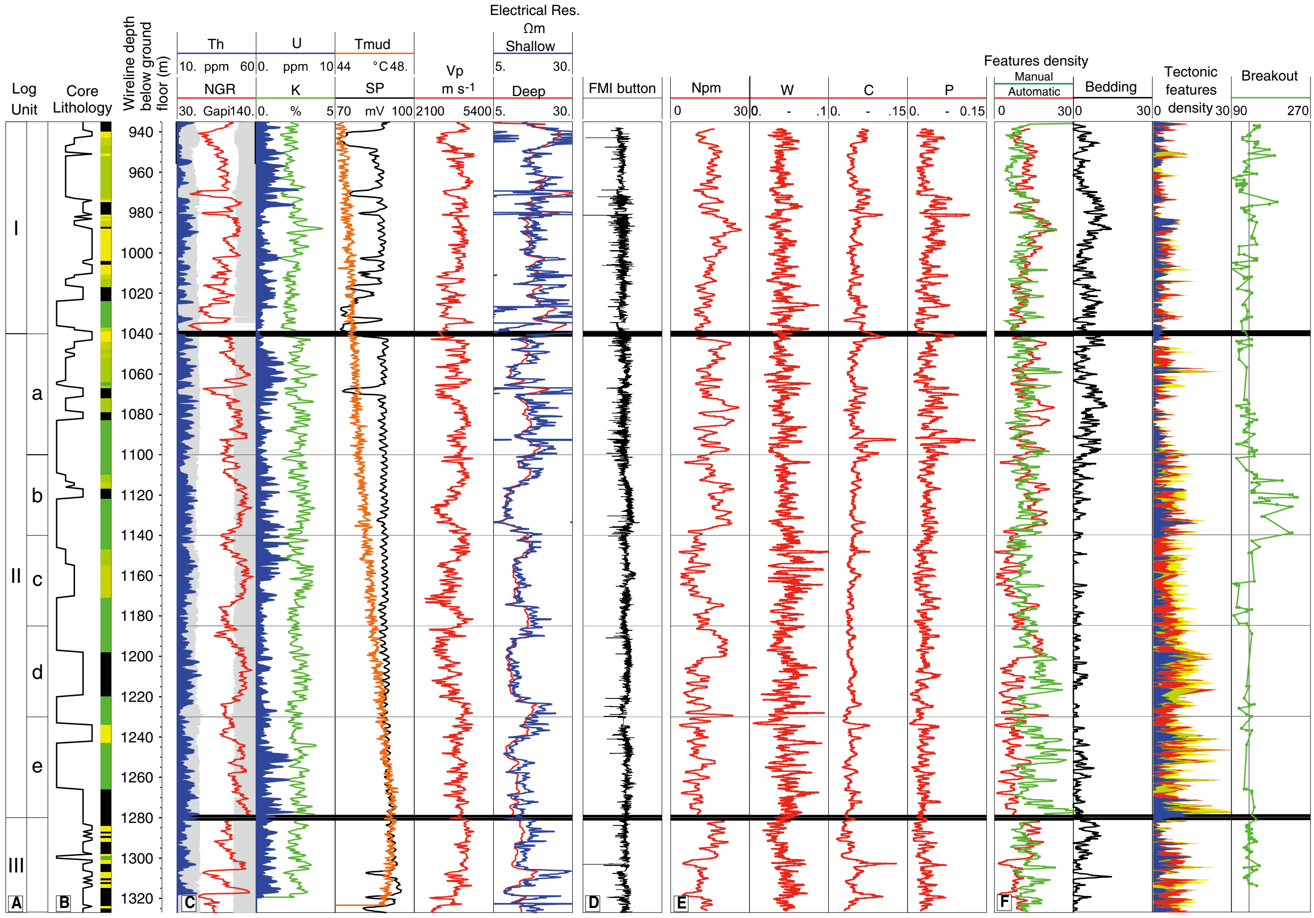

Figure 4. ICDP Taiwan Continental Drilling Project Hole B. [A] log units; [B] core units and lithology inferred from core data; [C] standard scalar logs: natural gamma radiation (NGR), thorium (Th), uranium (U), potassium (K), mud temperature (Tmud), spontaneous potential (SP), sonic velocity (Vp), shallow and deep electrical resistivities; [D] one button Fullbore Formation MicroImager (FMI) microresistivity log; [E] averaged density (Npm), size (W), electrical contrast (C) of detected features (singularities in microresistivity log) and product P (P = Npm x W x C); [F] density of sedimentary beds and structural features and orientation of breakouts recognized from visual analysis of the FMI images.

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http://dx.doi.org/10.2973/odp.proc.ir.176.1999

http://www.scec.org/instanet/01news/es_abstracts/Iturrino_et_al.pdf

Co-author **Dr. Tim Brewer** collapsed and died on Saturday morning, 14th July, 2007, while attending a conference in Barcelona. This is obviously shocking and very sad news and came as a complete surprise to everyone.

Tim was a senior member of staff in the Department of Geology at the University of Leicester but also the lead coordinator in the European Petrophysical Consortium, part of the ECORD Science Operator for the Integrated Ocean Drilling Program.

He will be sadly missed by his friends and colleagues around the world.

On the Fidelity of "CORK" Borehole Hydrologic Observatory Pressure Records

by Earl Davis and Keir Becker

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Introduction

Long-term formation pressure monitoring in Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) boreholes using evolving Circulation Obviation Retrofit Kit (CORK) hydrologic observatory technology has led to unanticipated applications as a result of the growing duration of recording intervals and the improvement of measurement fidelity. Current capabilities provide geologically meaningful observations over a broad range of time scales from static state to 1 Hz, allowing investigations of many coupled hydrologic, geodynamic, and seismologic phenomena. In this review, we present observations that provide constraints on current limits to recording fidelity, and examples of how leakage can affect pressure observations.

Background

The capability to seal and monitor the hydrologic state of deep-ocean boreholes drilled by the ODP was developed in 1990, and since that time, a broad range of experiments using this technology has been carried out to study the hydrogeology of ridge axes, older oceanic crust, and accretionary and non-accretionary subduction prisms. Original "CORK" installations (Fig. 1) employed a seal at the top of a standard solid steel casing string to isolate a single window of interest at depth for pressure monitoring and fluid sampling (Davis et al., 1992). Subsequent refinements (Fig. 1) have allowed pressure monitoring and fluid sampling at multiple formational levels outside and below the casing (Mikada et al., 2002; Jannasch et al., 2003; Becker and Davis, 2005). In both configurations, temperature measurements can be made inside and below the casing. Monitoring in installations completed to date has led to the determination of the static formation state and the driving forces and rates of fluid flow as originally planned, as well as to unexpected new insights regarding elastic and hydrologic formation properties, and secular and episodic strain in a variety of geologic settings and over a broad range of temporal and spatial scales (Davis and Becker, 2004; Becker and Davis, 2005; Kastner et al., 2007). In this article, we present data excerpts that illustrate the current level of recording fidelity, and we review problems experienced with some of the installations. Examples are drawn primarily from ocean crustal Site 1026 recently instrumented with new high resolution instrumentation, and sedimentary Sites 1173 and 808 at the Nankai subduction zone. While significant new insight has been gained through temperature monitoring and continuous fluid sampling, we limit this discussion to the measurement of pressure.

Theoretical Limits to Resolution

Limits to data quality are imposed by the characteristics of the measuring devices employed, and by the hydraulics of the CORK systems in context of the formations in which they are installed. All CORK systems deployed to date have been equipped with absolute pressure sensors (Paroscientific, Inc.) that utilize a quartz transducer loaded by the ocean- or formation-water pressure via a Bourdon tube. The pressure-sensitive oscillation frequency of the transducer crystal is determined by comparing its output signal to a fixed reference frequency. Early electronics employed an integer cycle counter and provided a resolution of roughly 1 ppm full-scale at 1 Hz. In practice, memory and battery capacity limited sampling intervals to 1 hr early in the development history, and this was later refined to 10 minutes. The intrinsic characteristics of the transducers allow much higher resolution to be achieved, and a recently developed fractional period counter (Bennest Enterprises, Ltd.) allows pressure to be

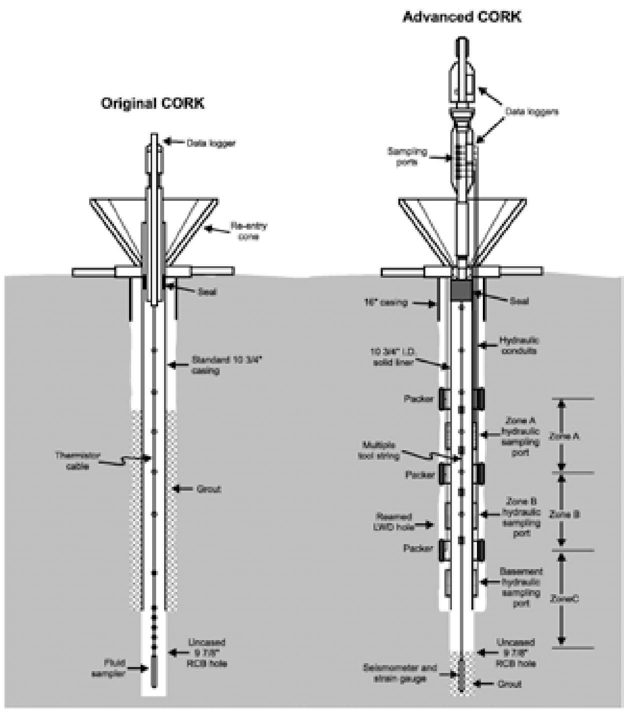

Figure 1. Schematic illustrations of original CORK and advanced CORK plumbing configurations for measuring ocean and formation pressure with sensors at the seafloor.

determined to a few tens of ppb (~2 Pa, or 0.2 mm of equivalent water head) at 1 Hz. Autonomous deployments are still restricted to measurement frequencies lower than this, but instruments equipped with Bennest fractional-period counters soon to be connected to seafloor power and communications cables will allow full use of this "high-frequency" resolution. The highest autonomous sampling rate employed to date (15 s sample period at Site 1026) shows oceanographic signal levels approaching the theoretical limit (Fig. 2A).

At the low-frequency end of the spectrum, fidelity limits are imposed by sensor drift. Seafloor records from Sites 808 and 1173 (located 13 km from one another) show rates of drift that decrease from ~5 kPa yr^{-1} in the first few months after deployment, to ~0.1 kPa yr^{-1} over longer periods of time (Fig. 2B). Other sites show a similar behavior. Detection of natural secular change of formation pressures or water depths at rates less than this requires periodic calibration checks with a mobile sensor. Intermediate-period (<1 yr) oceanographic signals (Fig. 2B) also impose limits on detecting tectonic signals, although local stable reference sites can help to overcome this problem.

Hydraulic-system limits on fidelity originate primarily from the inability of the formation to deliver or receive fluid rapidly enough to accommodate compliance in the CORK plumbing as formation pressure changes. The most influential formation and CORK system properties are hydraulic storage compressibility and permeability, and plumbing volume and fluid compressibility, respectively. Original CORKs utilized the full volume of the cased holes to transmit formation pressure to the sensors at the seafloor (Fig. 1). A significant reduction in the system fluid volume and associated compliance was gained by later CORKs (collectively referred to herein as "advanced CORKs", or ACORKs) which used small-diameter hydraulic lines running from the sensors to relatively small-volume permeable formation screens (Fig. 1; Table 1). Compliance of the all-steel plumbing components is negligible relative to the water they contain. Entrained gas can strongly affect the plumbing compressibility, but purging during (and often after) deployment has been done to reduce or eliminate this factor. Hydraulic resistance and compliance in the annulus outside the casing screens in sedimentary sections are difficult to assess, but they are probably insignificant, since low sediment strength does not allow the formation to support its overburden, and collapse around the screens is likely to be complete and benign. A discussion of these factors and their possible influence on the frequency response of CORK systems is provided by Sawyer et al. Dependence of the system response on the primary factors of sediment compressibility, permeability, and CORK-system compliance, can be understood using a formulation of Bredehoeft and Papadopulos (1980) for well-bore response to a step-wise change in formation pressure. Parameters that cover the range of CORK installations are provided in Table 1, and the results are summarized in Fig. 3. In Fig. 3A, dimensionless time incorporates scaling for formation permeability and compressibility; when converted to real time (Fig. 3B), the orders-of-magnitude difference in sediment and basalt permeabilities result in much faster response times for a CORK in basalt compared to a CORK in sediment, despite the fact that their type curves are similar (Fig. 3A). The differences among the type curves also involves a scaling for system volume, leading to a much faster actual response time for an ACORK vs. a CORK in sediment (Fig. 3B).

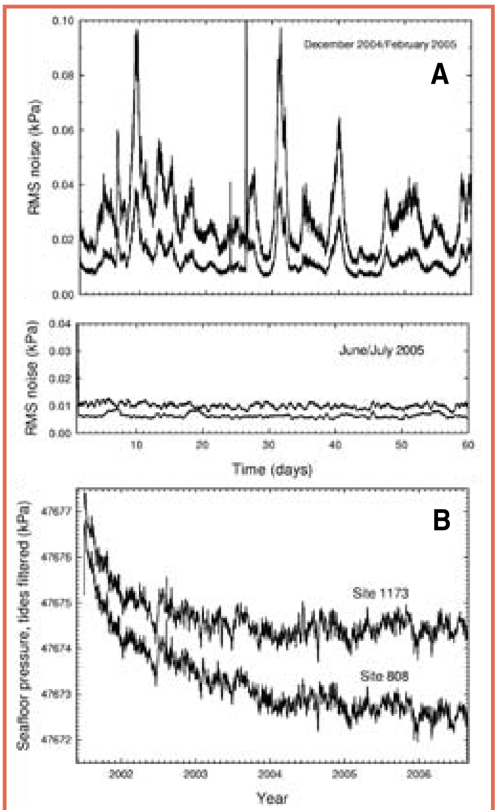

Figure 2. Indications of high recording fidelity from oceanographic signals. [A] Typical RMS high-frequency (<5 min period) seafloor- and formation-pressure signal levels at ODP Site 1026 in stormy and calm periods. Short bursts of high amplitudes in late December are teleseismic in origin (e.g., Fig. 5a). [B] Seafloor pressure records from ODP Sites 808 and 1173 (filtered to eliminate tidal and higher frequency signals) are dominated by slowly decaying sensor drift and intermediate-period oceanographic signals.

Observational Indications of High Data Quality

The best examples of current intrinsic recording capability at high frequencies are provided by a new-generation (Bennest fractional period counter) instrument installed on the Juan de Fuca Ridge flank in Hole 1026B in 2004 during IODP Expedition 301. This modified (Fisher et al., 2005) CORK samples highly permeable oceanic crust, and CORK system effects are probably small (Fig. 3B). Time-series data suggest uniform elastic formation response to oceanographic loading over a broad range of frequencies (Fig. 4). A slight flattening of the seafloor- and formation-pressure power spectra at high frequencies may indicate approach to the sensor noise floor, although this is not surprising, given that the high-frequency signal levels during oceanographically quiet times are only ~10 Pa, i.e., close to the 2 Pa measurement resolution (Fig. 2A). Other indications of recording fidelity at high frequency have been provided by signals of geologic origin. An example of pressure signals from the Sumatra earthquake of 2004 includes seismic body waves that are smaller in amplitude in the for-

Table 1. Range of parameters for formation and CORK system properties (500 m hole assumed)

Property	CORK in basalt	CORK in sediment	ACORK in sediment
Fluid compressibility	0.4×10^{-9} Pa^{-1}	0.4×10^{-9} Pa^{-1}	0.4×10^{-9} Pa^{-1}
Formation compressibility	10^{-9} Pa^{-1}	10^{-8} Pa^{-1}	10^{-8} Pa^{-1}
Permeability	10^{-10} m^2	10^{-18} m^2	10^{-18} m^2
Fluid viscosity	0.4×10^{-3} Pa s	0.4×10^{-3} Pa s	0.4×10^{-3} Pa s
System volume	30 m^3	30 m^3	0.064 m^3
Window length	50 m	50 m	7.6 m
Window radius	0.15 m	0.15 m	0.15 m
Porosity	0.1	0.4	0.4
Storage compressibility	1.04×10^{-9} Pa^{-1}	1.02×10^{-8} Pa^{-1}	1.02×10^{-8} Pa^{-1}

mation than in the water column, and surface waves that are larger in the formation (Fig. 5A). The formation/seafloor amplitude ratio for the P waves is consistent with that for ocean waves and tides (~0.3). The amplitude ratio for the surface waves (~2.5) is much larger.

As yet, no high resolution instruments have been installed in any sedimentary formations, and the limits of the old-generation instruments do not allow oceanographic signals to be used to assess the point at which CORK or ACORK hydraulic systems filter high-frequency hydrologic signals. Signals of geologic origin do provide relevant information. Observation of a static strain step recorded at Site 1173 (Fig. 5b) provides confidence that this low-system-volume ACORK provides reasonable high-frequency fidelity, despite the low formation permeability. Response to what is probably a step-wise change in formation pressure (reflecting coseismic volumetric contraction; Davis et al., 2007) is rapid (≤10 minutes, as predicted by Fig. 3). Seismic waves are also seen in this record, although the 10-min sampling interval causes the recorded signal to be highly aliased. In the future, higher resolution and higher sampling frequency will allow the full system fidelity to be properly examined.

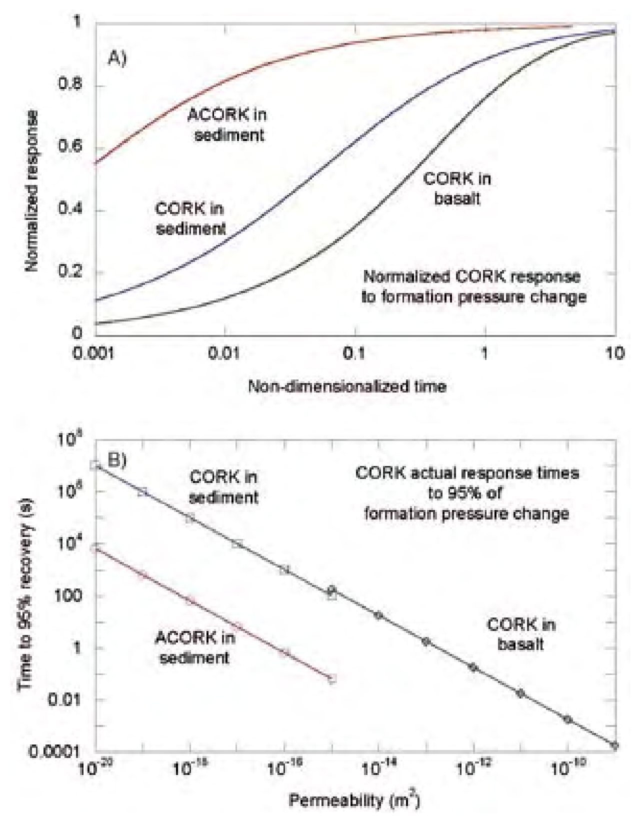

Figure 3. Simulated CORK and ACORK system response to a step change in formation pressure. [A] Characteristic Bredehoeft and Papadopulos (1980) type-curves for three example configurations (see parameter values in Table 1). [B] Dependence on formation permeability of actual CORK response times to 95% of the formation pressure change i.e., when curves reach 0.95 in [A].

Pitfalls

While CORK pressure monitoring to date has been generally very successful and the fidelity generally high, hydraulic leakage caused by physically damaged, hydrothermally deteriorated, or missing seals has impaired the fidelity of monitoring at several sites. Where leaks occur, measured formation pressure can be affected directly by pressure loss through the leaks, although most problems have arisen indirectly through effects of thermal buoyancy and thermal expansion associated with steady or transient flow up or down the leaking borehole along the geothermal gradient. A record from Site 1025 on the Juan de Fuca Ridge flank (Fig. 6a) illustrates a case where thermal buoyancy contributes most to a leakage-induced pressure perturbation. When a fluid sampling valve was opened, the record became noisy, the tidal signal was distorted, and the static pressure rose above the natural formation pressure as a consequence of the buoyancy of the warm discharge through the CORK casing from the slightly super-hydrostatic formation. Such perturbations arise whenever pressures are measured in high-permeability formations in the presence of leaks.

A different effect has been witnessed in two ACORKs that penetrate low-permeability sediments, namely Site 1173, where fluid sampling valves connected to some of the umbilical tubes were manipulated during monitoring, and Site 808, where pressures in multiple screens were affected by flow inside the casing from a permeable fault zone at depth. In this latter instance, a plug was to have been installed inside the main casing (Fig. 1), but drilling difficulties precluded this operation. Most of the screens appear to have been hydrologically well isolated and coupled to the formation at this site, but there was no check against flow up the inside of the casing from its bottom end. Several initially puzzling observations can be explained by thermal expansion and contraction of fluid in the lines and in low-permeability parts of the formation outside the screens caused by variable heating and cooling by the unwanted vertical flow:

Tidal loading response: The first of these observations is the occurrence of unusual formation tidal signals. Normally, formation response should reflect elastic deformation of the formation matrix under the influence of seafloor loading, with little or no phase between the loading and response. Given the compressibility of the sediments at Nankai (Bourlange et al., 2005), the amplitude of the formation pressure signal should be reduced to roughly 90% of that at the seafloor (Wang and Davis, 1996). In several instances, very unusual response is seen relative to these expectations. During part of the early history of recording at the deepest screen at Site 1173 , when valves to higher screens were unintentionally left open, the amplitude of the formation tidal signal at the deepest screen actually exceeded that at the seafloor, and the sign was reversed (Fig. 6B). At Site 808, tidal signals at most of the screens are characterized by large phases and unreasonable levels of attenuation during most of the recording period (Fig. 6C). This behavior has been described in detail by Sawyer et al. who have attributed it to purely hydrologic interaction between the ACORK measurement system and the formation. Inexplicably large compliance in the ACORK plumbing and a large resistive "skin" effect at the screens are required to account for most of the behavior observed, however, and the signal amplification and sign reversal seen in Fig. 6b cannot be accounted for in this way at all.

High-frequency noise: Another noteworthy characteristic of the records from Site 808 is the persistence of high frequency pressure variations riding on the tidal signal that are highly correlated among multiple levels (Fig. 6C). The magnitude of this noise is consistently greatest for those screens that display the most anomalous tidal response. Whatever the source of this noise, it must act consistently over the full section of the hole to produce the coherence observed.

"Cross-talk": A third observation that provides key evidence for thermal expansion effects is of apparent cross-talk between certain screens at Site 1173. This is particularly well illustrated by the example at the end of the record shown in Fig. 6D, when a small-diameter geochemical sampling line was opened for testing. This line is terminated in screen 4, and as expected, pressure measured in the parallel monitoring line connected to that screen fell slightly when the sampling valve was opened. At the same time, pressures in the lines terminating at screens 1 and 3 rose by an amount roughly ten times greater than the drop registered at screen 4. A similar but seemingly opposite interaction was witnessed when the monitoring line valves were closed in 2002. Pressures at screen 1 dropped at the time of valve closure by 80 kPa to a seemingly inexplicable sub-hydrostatic level at the time the valves to other lines in the umbilical were closed.

Strain transients: Perhaps the most enigmatic observation is of impulsive pressure transients observed at Site 808 at the times of two seismic events (Fig. 6E and 6F). The transients contrast with simultaneous step-wise changes in pressure observed at Site 1173 (e.g., Fig. 5B); the earlier transient pulse was initially interpreted to be a signature of near-field transient strain associated with slip on the decollement immediately beneath the observation screens (Davis et al., 2006). This interpretation is almost certainly wrong.

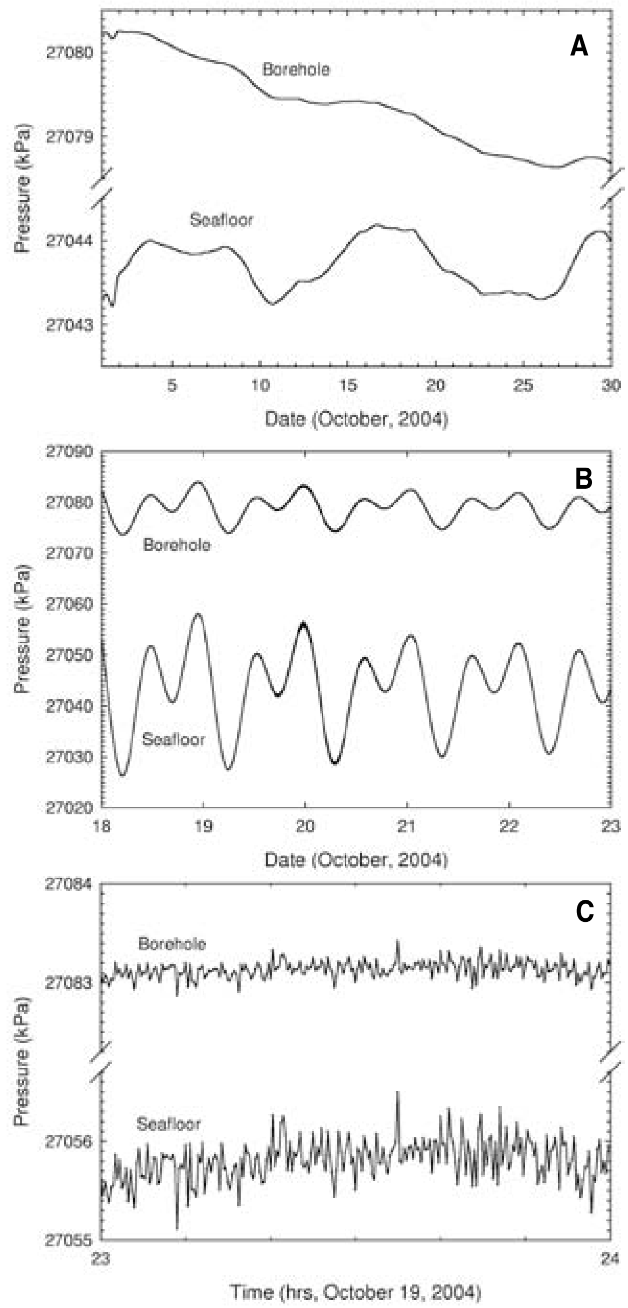

Figure 4. Typical formation-pressure response to [A] long-period, [B] tidal, and [C] infragravity sea-surface wave loading observed with a high resolution monitoring instrument at ocean crustal Site 1026.

All of these unusual observations can be accounted for by a single mechanism—thermal expansion and contraction of water in the umbilical tubing and screens and in the formation surrounding the screens, caused by variable vertical fluid flow inside the large diameter casing (Site 808) and in the opened sampling/monitoring lines of the hydraulic umbilical (Site 1173). Given the large contrast between the

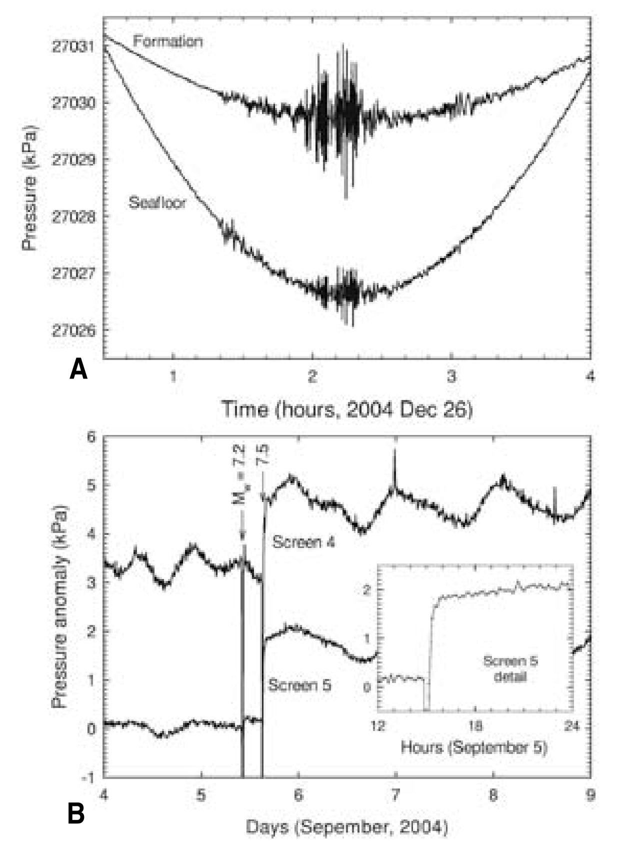

Figure 5. Indications of high recording fidelity from geologic signals. [A] Seismic waves from the December 2004 Sumatra Mw=9.0 earthquake. [B] Pressure steps observed in the sediments of the Philippine Sea plate off the Nankai subduction zone caused by regional volumetric strain associated with seismogenic rupture of the oceanic plate 220 km to the northwest off the Kii peninsula, Japan (Davis et al., 2007).

thermal expansivity and volumetric compressibility of water (~0.4 x 10^{-3} K^{-1} and ~0.4 x 10^{-9} Pa^{-1}, respectively), temperature sensitivity is inevitable wherever screens are well coupled to low-permeability sediments (like those of the lower Shikoku basin facies). The contrast yields a sensitivity of pressure to temperature of roughly 1 kPa mK^{-1}. Pressures may be produced with this efficiency if the temperature variation is coherent along the full distance from the screens to the sea-floor (an inevitable outcome of flow up or down the geothermal gradient), and if the sediment permeability at a given screen is sufficiently low to prohibit drainage at the rate of volumetric expansion. Whether this condition is met can be evaluated by considering the contrast between the thermal diffusivity (~10^{-7} m^2 s^{-1}) and the hydraulic diffusivity. Thermal diffusion can indeed outpace hydrologic diffusion in sediments like those of the Lower Shikoku Basin facies, which have a hydraulic diffusivity of ~2.5 × 10^{-9} m^2 s^{-1} (Bourlange et al., 2005; Gamage and Screaton, 2005; Table 1). Some inefficiency will result from thermal expansion of the tubing itself, and from the attenuation and time lag of thermal diffusion between the source of the thermal perturbation and the umbilical tube, screen, or sediment where the consequences of expansion are observed. The first factor is insignificant, given the large contrast in expansivity between water and steel. The importance of the second will vary with the frequency of the signal and with the time constant for the

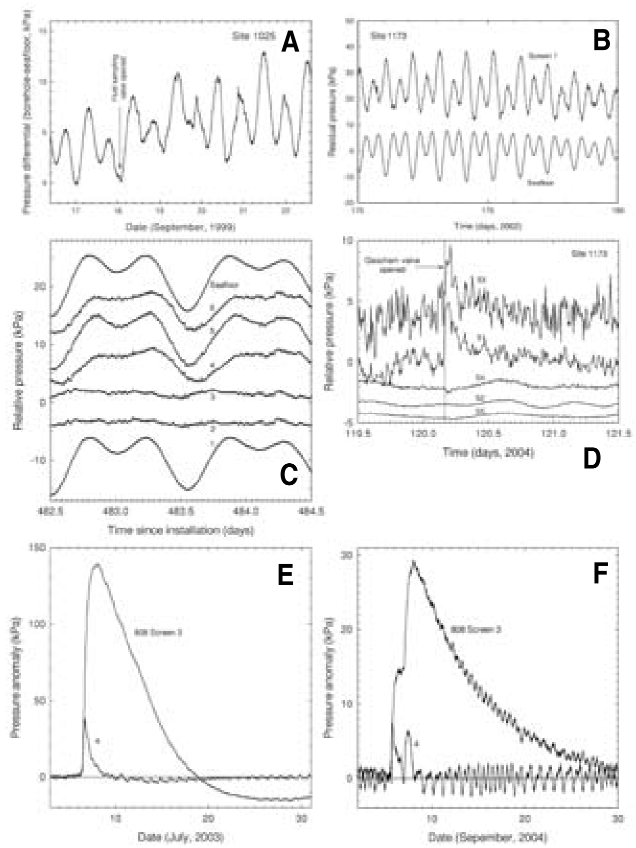

Figure 6. Indirect consequences of CORK-system leakage resulting from buoyancy [A] or thermal expansion effects (B–F) in high and low-permeability formations, respectively. [AF] Pressure before and after the opening of a fluid sampling valve at ocean crustal Site 1025. [B] Seafloor and formation pressures at Site 1173. During this time, the monitoring line to screen 1 was closed, but others were opened, allowing flow and thermal perturbations within the hydraulic umbilical. [C] Enigmatic tidal signals and coherent noise at Site 808 associated with flow inside the unsealed casing. [D] "Cross-talk" at Site 1173 when a geochemical sampling line leading to screen 4 was opened. [E] Transients recorded at Site 808 during fault-slip events in 2003 off Cape Muroto and [F] in 2004 off the Kii peninsula, Japan. Parts of the initial rises are the direct consequence of strain, but most of the signals are indirect thermal consequences of water expelled up the inside of the unsealed casing during the strain events.

thermal path (e.g., ~1 hr for conduction between the inside of the 10.75" casing and the formation, screens, or umbilical outside, and ~1 min for conduction between tubes within the umbilical).

Summary and Recommendations

The fidelity of CORK formation pressure records appears to be high over a broad frequency range. After pressure transducers equilibrate to ambient pressure, long-term drift is typically about 0.1 kPa yr^{-1}. Response at high measurement frequencies (a few Pa at 1 Hz) is good in high permeability formations, but CORK-system compliance may influence the fidelity of observations in very-low-permeability lithologies, even with the low-system-volume advantage offered by ACORK configurations.

Several lessons have been learned through inevitable installation errors, and these should be highlighted.

1) Consequences of leakage can degrade fidelity over a broad frequency range and they can be difficult to discriminate from real signals. A good example of this is provided by impulse transients witnessed at two strain events at the Nankai accretionary prism (Figs. 6E, 6F) which are now believed to be the result of umbilical- and formation-fluid thermal expansion caused by strain-induced flow inside the unsealed casing.

2) Leakage can be efficiently assessed by the measurement of temperature. At Nankai, installation of temperature sensors was planned, but was precluded by the same operational problem that prevented the installation of an internal casing seal. Great care must be used in the future to prevent and detect leaks.

3) Entrained CORK fluid volume should be minimized and screen area maximized to enhance the inherent system fidelity by reducing the time constant associated with the coupling between the measurement system and the formation. This will have the added benefit of reducing the geochemically perturbing effects of "foreign" water.

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Aurora Borealis – Development of a New Research Icebreaker with Drilling Capability

by Nicole Biebow and Jörn Thiede

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Introduction

The International Polar Year (IPY), with its attempts to coordinate and foster cooperation on an international level in an unprecedented way, offers a unique chance for a leap of progress in our understanding of polar processes and their dynamics with their influence on the adjacent continents and the global environment. However, polar research both on land and in the sea cannot achieve the progress needed without novel and state of the art technologies and infrastructure.

There are many novel tools presently being developed for polar research. In this report we will concentrate on the planning for a new research icebreaker, *Aurora Borealis* (Fig. 1), with an all-season capability of endurance in permanently ice-covered waters and with the possibility to carry out deep-sea drilling in ice-covered basins.

Scientific Relevance of the *Aurora Borealis* Project

Polar research and, in particular, the properties of northern and southern high latitude oceans are currently a subject of intense scientific debate and investigations, because they are (in real time) and have been (over historic and geologic time scales) subject to rapid and dramatic climatic variations. Polar regions react more rapidly and intensively to global change than other regions of the Earth. Examples of these modern changes include news about shrinking of the Arctic sea-ice cover (potentially leading to an opening of sea passages to the north of North America and Eurasia, and in the long run to a "blue" Arctic Ocean) and news about the calving of giant table icebergs from the ice shelves of Antarctica. Until now it has not been clear how many of these profound shifts in all parts of the Arctic are natural fluctuations or are due to human activity. Since this is a phenomenon occurring over decades, long time data series of atmospheric and oceanic conditions are needed for its understanding and prediction of its further development.

Global climate models demonstrate the importance of the polar areas in forcing of the ocean/climate system. The presence or absence of snow and ice influences global heat distribution through its effect on the albedo, and the polar oceans are the source of dense, cold bottom waters, which influence thermohaline circulation in the world oceans. This global conveyor is a major determinant of Earth's climate.

Despite the strong seasonality of polar environmental conditions, research in the central Arctic Ocean up to now could essentially only be conducted during the summer months, when the Arctic Ocean is accessible only by the strongest research icebreakers.

In spite of the critical role of the Arctic Ocean in climate control, it is the only sub-basin of the world's oceans that has essentially not been sampled by the drill ships of the Deep-Sea Drilling Project (DSDP) or the Ocean Drilling Program (ODP), and its long-term environmental history and tectonic structure is therefore poorly understood. Exceptions are the ODP Leg 151 and the more recent Integrated Ocean Drilling Program's (IODP) Expedition 302 (Arctic Coring Expedition, ACEX, within the central Arctic; Myhre et al., 1995; Moran et al., 2006). The lack of data represents one of the largest gaps of information in modern Earth science (Nansen Arctic Drilling Program, 1992, 1997), also relevant for the field of hydrocarbon exploration. Therefore, the new research icebreaker *Aurora Borealis* (Fig. 1) should be equipped with proper drilling facilities to drill in deep, permanently ice-covered ocean basins. The icebreaker must also be powerful enough to keep station against the drifting sea-ice cover and will have to be equipped with dynamic positioning.

The *Aurora Borealis* project impacts on two scientific communities which in part overlap in interests. The first one is

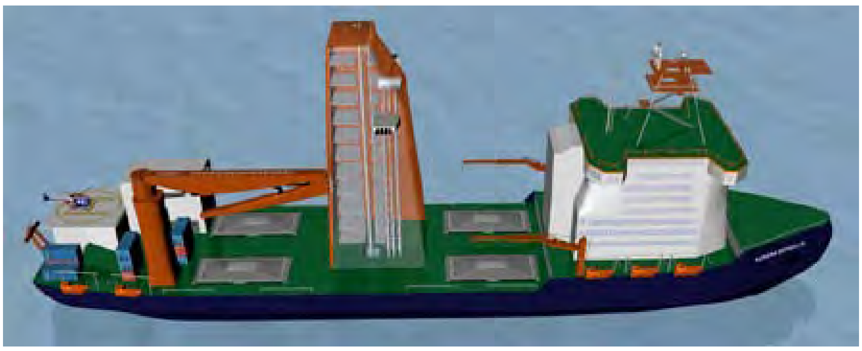

Figure 1. Initial design of the Aurora Borealis

Figure 2. Aurora Borealis will have two moon pools for drilling and the deployment of ROVs or similar devices.

the general polar science community that requires a ship for conducting year-round field and marine work and has a wide spectrum of scientific perspectives. The second is the deep-sea drilling community that would use the ship mainly during the summer months with optimal ice conditions to study the structure and properties of the crust below the Arctic Ocean and to unravel the history of environmental and climate changes. While the ACEX expedition in 2004 is the only case of high Arctic drilling, substantial progress has been made around Antarctica by the drilling platforms of the DSDP and ODP during ice-free seasons. Also, deployment of small drill rigs from sea-ice very close to shore (ANDRILL, Cape-Roberts-Project) and shallow drilling from the icebreaker *R/V Nathaniel B. Palmer* (SHALDRILL) have taken place.

The scientific objectives of the *Aurora Borealis* project are outlined in the "Science Perspective", published under the same name by the European Polar Board (EPB) of the European Science Foundation (ESF) in collaboration with ECORD (European Consortium of Ocean Research Drilling). A detailed accounting of the scientific objectives and research prospects can be found in these documents (Thiede and Egerton, 2004).

Technical Details

The research icebreaker *Aurora Borealis* will be the most advanced polar research vessel in the world with a multi-functional role of drilling in deep ocean basins and supporting climate/environmental research and decision support for stakeholder governments for the next few decades. The new technological features will include azimuth propulsion systems, satellite navigation, ice-management support, and the deployment and operation of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) from the twin moon pools (Fig. 2). The most unique feature of the vessel is the deep drilling rig, which will enable sampling of the ocean floor and sub-sea in up to 4000 m of water and with 1000 m penetration at the most inhospitable places on Earth. In the long term the drilling capability will be deployed in both polar regions, and *Aurora Borealis* will be the only vessel worldwide that could undertake this type of scientific investigation. The possibility to flexibly equip the ship with laboratory and supply containers, and the variable arrangement of other modular infrastructure (in particular, winches, cranes, etc.), free deck-space, and separate protected deck areas, will allow the planned research vessel to cover the needs of most disciplines in marine research, including the capability to carry out geophysical investigations (seismic reflection and refraction, gravity, magnetic, swath bathymetry mapping system, sediment echo sounder). The ship can be deployed as a research icebreaker in polar seas because it will meet the specifications of the highest ice-class for polar icebreakers. The vessel will be a powerful research icebreaker with 44,000 tons displacement and a length of 196 m, with 50-megawatt azimuth propulsion systems. It will have high ice performance to penetrate autonomously (single ship operation) into the central Arctic Ocean with 2.5 meters of ice cover, during all seasons of the year. A large fuel capacity is required because of the excessive power requirements for drilling and maintaining station in the central Arctic (or other severely ice covered waters) during what are envisaged to be long expeditions. This factor is decisive for the large size of the ship. The construction of *Aurora Borealis* requires several new technical solutions and will provide an extended technical potential and knowledge for marine technologies and the ship building industry

Perspectives of the *Aurora Borealis* Project

Many northern nations have a particular interest in understanding the Arctic environment with its high potential for environmental change in response to global warning. In addition, considerable living and non-living resources are likely to be found below the Arctic Ocean and its adjacent continental margins. However, modern research vessels capable of penetrating into the central Arctic are few and mostly inadequate. Therefore, a new state-of-the-art research icebreaker is urgently required to fulfill the needs of polar research. This new icebreaker would be conceived as an optimized and multi-national science platform from the keel up and will allow long international and interdisciplinary expeditions into the central Arctic Ocean during all seasons of the year.

An efficient use of this icebreaker requires the formation of a consortium of several countries and a substantial build-up of their polar research institutions to ensure an efficient employment of the research vessel during all seasons of the year. Extensive and well-developed Arctic research programs exist in several countries, particularly in the Scandinavian countries, the U.S.A., Russia, and Germany. Each country has different organizations or working groups with rather diverse structures. The construction of *Aurora Borealis* as a joint European/international research icebreaker would result from a considerable commitment of the participating nations to coordinate and expand their polar research programs to operate this expensive ship continuously and with the necessary efficiency. *Aurora Borealis* would contribute to meet the Arctic drilling challenge within IODP; however, in a long-term perspective the *Aurora Borealis* would also be used to address Antarctic research targets, both in its mode as a regular research vessel as well as a polar drill ship.

European Strategy Forum on Research Infrastructures ESFRI

EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

Report 2006

	Projects (in alphabetical order per discipline)	Estimated Construction Cost (M€) *	First possible operations for users	Indicative Operational/ Deployment Cost (M€/year)
Environmental Sciences	AURORA BOREALIS	360	[illegible]	[illegible]
	[illegible]	150	2011	[illegible]
	[illegible]	50 - 100	[illegible]	2–4
	[illegible]	76	[illegible]	[illegible]
	[illegible]	20	[illegible]	[illegible]
	[illegible]	255	[illegible]	[illegible]
	LIFE WATCH	370	[illegible]	[illegible]

* [illegible]

Figure 3. ESFRI Roadmap 2006 of the European Commission (http://www.eubuero.de/arbeitsbereiche/infrastrukturen/esfri/Download/dat_/fil_2076).

The German Science Council evaluated the *Aurora Borealis* project in May 2005 and recommended the construction of the research icebreaker in 2006. Since March 2007 the German Federal Ministry for Science and Education (BMBF) has been funding a portion of the preparatory work for *Aurora Borealis*. In this project the final engineering work for the development of the vessel is carried out under coordination of the Alfred-Wegener-Institute and the University of Applied Sciences in Bremen. Additionally, the engagement of the European science community will be promoted by organizing workshops in different European countries to discuss science plans and technical requirements for the *Aurora Borealis*.

The European Commission identified the project for the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap (Fig. 3). The Commission found that it reached the highest scientific priority for developing this large-scale infrastructure for basic research in Europe. A European consortium of sixteen institutions, funding agencies, and companies from eleven European nations including Russia has already formed to develop management structures for this unique facility and to implement it into the European Research Area.

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Related Web Link

http://www.eubuero.de/arbeitsbereiche/infrastrukturen/esfri/Download/dat_/fil_2076

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Scientific Drilling with the Sea Floor Drill Rig MeBo

by Tim Freudenthal and Gerold Wefer

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Introduction

In March 2007 the sea floor drill rig MeBo (short for "**Me**eresboden-**Bo**hrgerät", 'sea floor drill rig' in German) returned from a 17-day scientific cruise with the new German research vessel *Maria S. Merian*. Four sites between 350 m and 1700 m water depth were sampled at the continental slope off Morocco by push coring and rotary drilling. Up to 41.5-m-long sediment cores were recovered from Miocene, Pliocene, and Pleistocene marls. MeBo bridges the gap between conventional sampling methods from standard multipurpose research vessels (gravity corer, piston corer, dredges) and drill ships. Most bigger research vessels will be able to support deployment of the MeBo. Since the drill system can be easily transported within 20-ft containers, worldwide operation from vessels of opportunity is possible. With the MeBo a new system is available for marine geosciences that allows the recovery of high quality samples from soft sediments and hard rock from the deep sea without relying on the services of expensive drilling vessels.

Rationale

A variety of research targets in marine sciences—including gas hydrates, mud mounds and mud volcanoes, ore formation, and paleoclimate—can be addressed by shallow drilling (30–100 m below sea floor) in the deep sea (Quinn and Mountain, 2000; Sager et al., 2003; Herzig et al., 2003). In general, standard sampling tools like gravity corers or dredges only allow recovery of fairly short cores from soft sediments or fragments of bedrock lying on the sea surface. Drill ships providing deeper penetration are expensive and typically booked far in advance, if available at all; therefore at the Marum Center for Marine Environmental Sciences (Marum) at the University of Bremen we developed the drill rig MeBo (Freudenthal and Wefer, 2006) that can be deployed from standard research vessels.

System Concept

The MeBo is deployed on the sea bed and is remotely controlled from the vessel (Fig.1). The rig is lowered to the sea bed using a steel-armored umbilical with a diameter of 32 mm. The deployment depth is currently limited to a maximum of 2000 m below sea level by the length and strength of the umbilical. Four legs are extended before landing to increase the stability of the rig (Fig. 2). Copper wires and fiber optic cables within the umbilical are used for energy supply from the vessel and for communication between the MeBo and the control unit on the deck of the vessel, respectively. The drill rig is powered by four hydraulic pumps that are driven with electric motors. A variety of sensors, video cameras, and lights are used for monitoring the drill performance.

The mast with the feeding system forms the central part of the drill rig (Fig. 2). The drill head provides the required torque and rotary speed for rock drilling; it is mounted on a guide carriage that moves up and down the mast with a maximum push force of 4 tons. A water pump provides sea water for flushing the drill string, for cooling of the drill bit, and for removing the drill cuttings. The system utilizes commercial rotary core barrels with diamond or tungsten carbide bits. In addition it can push core barrels into soft formations, and case the boreholes.

The MeBo stores drilling rods, casing tubes, and push-coring and rotary barrels on two rotating magazines that

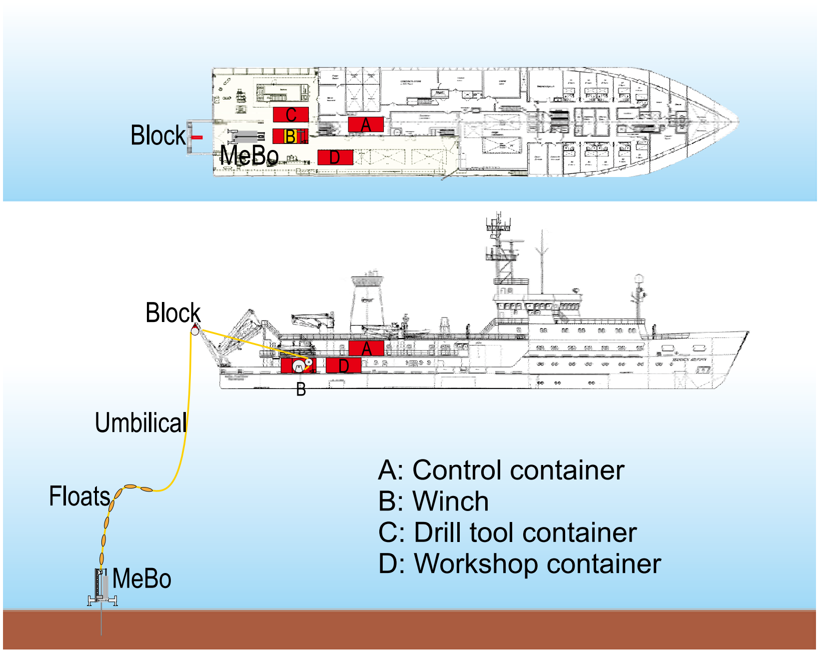

Figure 1. Schematic deployment scheme of the sea floor drill rig MeBo exemplified for *RV Maria S. Merian.*

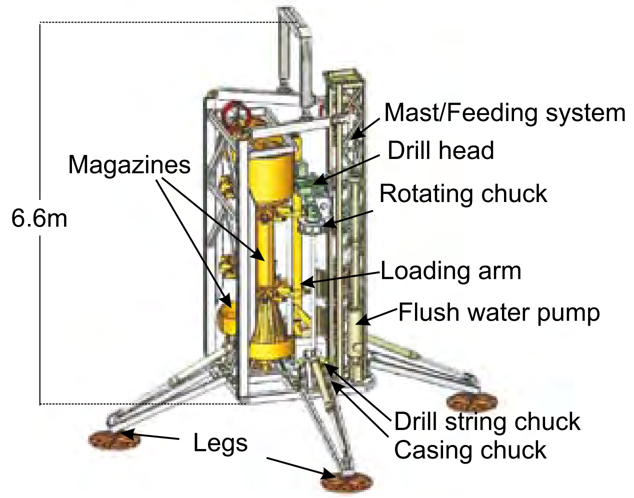

Figure 2. Overview of basic components of sea floor drill rig MeBo.

may be loaded with a mixture of tools as required for a specific task. The loading arm is used in combination with one rotating and two fixed chucks for building the drill string up and down. When drilling is started, a core barrel is taken off the magazine and loaded below the drill head. After the thread connection between barrel head and drill head is closed, the first three meters can be sampled. The barrel is then stored together with the drilled core in the magazine, and the next empty core barrel is lowered into the drilled hole. A 3-m rod is added, and the next three meters can be sampled. With a storing capacity of 17 barrels, 16 rods and 15 casing tubes, the MeBo has the capability to drill up to 50 m into the sea floor, to recover cores with 74–84 mm diameter, and to stabilize the drilled hole down to a depth of 40 m.

Easy transportation was a key requirement for the system design, since the MeBo is deployed worldwide from vessels of opportunity (Fig. 3). All parts belonging to the MeBo system, including control unit, workshop, a rack for the drill tools, and the winch, are containerized (Fig. 3). The MeBo unit fits into an open top high cube 20-ft container when the four legs are retracted. In addition, a launch and recovery system that was developed for the deployment of the MeBo from the German research vessel *Meteor* can be adapted to the deck configuration of other vessels. It, too, fits into a 20-ft open top container when dismantled. Altogether, the complete MeBo system is shipped within six 20-ft containers.

Development and Tests

Previous developments of sea bed drill rigs proved the advantages of drilling from a stable platform at the sea floor but demonstrated also the challenges of remotely controlled drilling and drill string handling (Johnson, 1991; Stuart, 2004). Only a few prototype systems of sea bed drill rigs, including the Rockdrill from the British Geological Survey, the Japanese BMS, and the Australian PROD (Portable Remotely Operated Drill), are operated worldwide, with only the PROD system capable of reaching drilling depths of more than 30 m. Since this system is dedicated to operations in the marine geotechnical survey industry (Stuart, 2004), we decided to establish a new development—the sea floor drill rig MeBo—optimized for the requirements and facilities for scientific investigations of the sea floor.

The development was realized at the Marum with support from a variety of national and international companies. Next to overall system design, project management, and system integration, the Marum Center was responsible for the sensors as well as control hardware and software of the system. Most of the mechanical and hydraulic parts of the drill rig were developed, manufactured, and assembled by Prakla Bohrtechnik GmbH (Peine, Germany), a company specializing in the fabrication of multi-purpose land drill rigs for core drilling and well installation. The energy supply and telemetry system were designed and delivered by Schilling Robotics (Davis, California), Hogenkamp (Lilienthal, Germany), and STA GmbH (Bremerhaven, Germany). Schilling Robotics also developed the rotating magazines and the loading arm. The umbilical was designed and manufactured by Norddeutsche Seekabelwerke (Nordenham, Germany), while the winch was delivered by MacArtney (Esbjerg, Denmark).

After an engineering and construction phase of about one year, the system was tested successfully in July/August 2005 in deep water at the continental slope off Morocco with the German research vessel *Meteor* (Wefer et al., 2006). Within the following year, two further expeditions were conducted with the Irish research vessel *Celtic Explorer*: one for shallow

Figure 3. View of the work deck of *RV Meteor* during a deployment of the sea floor drill rig MeBo.

water tests of the MeBo system in the Baltic Sea, and a first scientific cruise on the Porcupine Bank west of Ireland for the Irish Shelf Petrol Studies Group (ISPSG) of the Irish Petroleum Infrastructure Programme Group 4.

During these two cruises, the MeBo was deployed twenty times between 20 m and 1700 m. Push coring for soft sediments and rotary drilling for hard rocks, as well as stabilization of the drilled hole by setting casings, were successfully accomplished. Altogether, 127 meters were drilled in sand, gravel, marl, till, conglomerates, breccia, granite, and gneiss, and 57.2 meters of core were recovered (Fig. 4). The recovery rate was especially good for hard rocks and consolidated cohesive sediments.

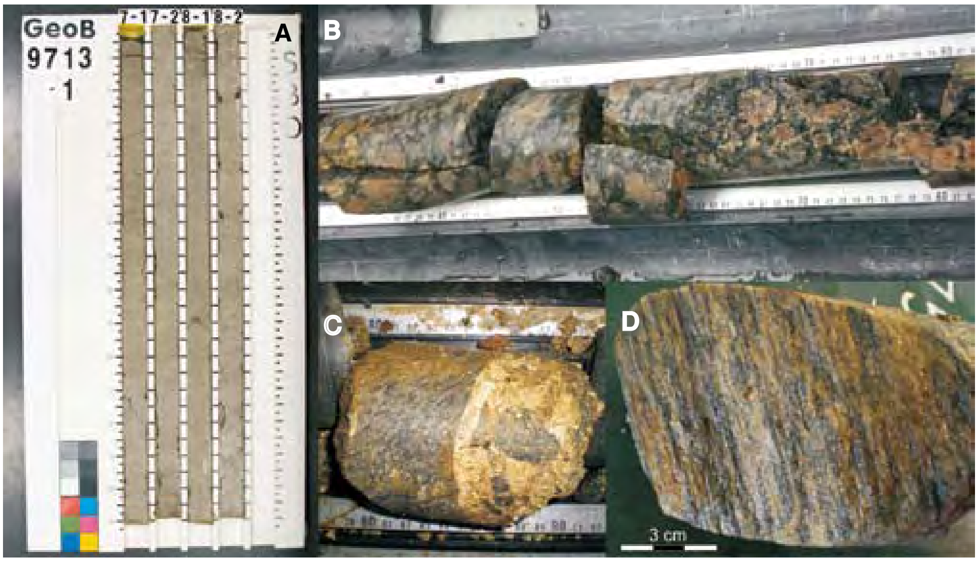

Figure 4. Examples of sea floor samples recovered with the sea floor drill rig MeBo. [A] consolidated pliocene marl, continental slope off Morocco; [B] granite, Porcupine Bank; [C] conglomerate, Porcupine Bank; [D] gneiss, Porcupine Bank.

Scientific Results of MSM04/4

In March 2007 the MeBo was deployed for the first time for paleoclimate research on the research vessel *Maria S. Merian* at the continental slope off Morocco (Fig. 5) with two major goals:


Figure 5. Launch of the sea floor drill rig MeBo from the *Maria S. Merian*.

1) Two sites with extremely high sedimentation rates of more than 80 cm kyr^{-1} were cored for high resolution records of abrupt climate changes during the last glacial period.

2) Two other sites were drilled at and near the former DSDP drilling site 369. A big slide at this part of the continental slope of Morocco allowed for direct sampling of sediments of Miocene age by shallow drilling.

Altogether we recovered approximately 154 meters of sediments at these four sites with a maximum drilling depth of 41.55 m and about 120 m core recovery. A highlight at the last drilling site was to recover within forty-eight hours a nearly 40-m-long sediment core of middle to late Miocene age, according to first shipboard nannofossil stratigraphy (Fig. 6). This time period is of special interest for paleoclimate research because it comprises large changes in carbon burial in deep-sea sediments as well as a major step in the formation of the East Antarctic continental ice shield (Vincent and Berger, 1985; Holbourne et al., 2005). Core recovery rate at this site (1720 m water depth) by rotary drilling with hard metal bits was about 100%. Without the services of the MeBo, it wouldn't have been possible to sample these Miocene consolidated marls from a standard research vessel like *RV Maria S. Merian*.

Outlook

With the development of the MeBo system, a substantial improvement of the sampling possibilities for the marine geosciences was achieved. For shallow drilling and coring, the MeBo provides a new and cost effective alternative to the services of drill ships. Worldwide, it is the only system available for marine geosciences that can reach drilling depths of up to 50 m from standard research vessels. MeBo also has the major advantage that the drilling operations are performed from a stable platform independent of any ship movements caused by waves, wind, or currents. Currently,

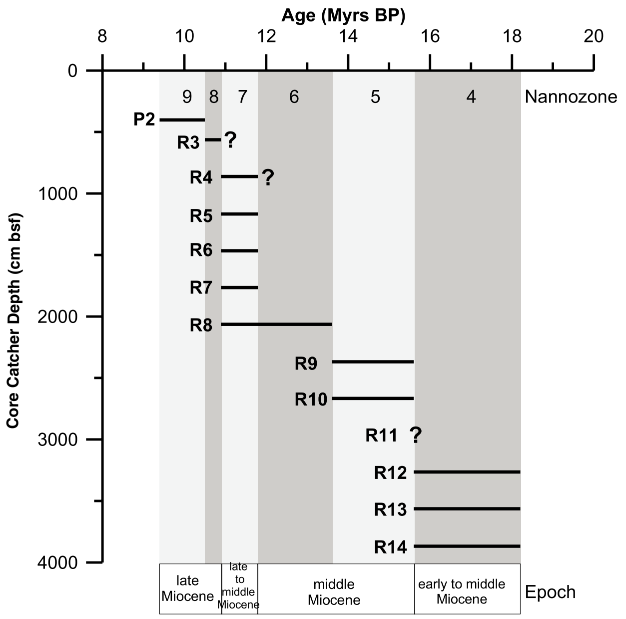

Figure 6. Preliminary shipboard nannofossil stratigraphy by Babette Böckel (unpublished) on core catcher samples at site GeoB11826-1 (26°35N, 14°59W, 1690 m water depth) following the nannofossil zonation established by Martini (1971). Barrel numbers are indicated by P (push coring) and R (rotary drilling).

we are working together with Prakla Bohrtechnik GmbH to upgrade the system to use wire-line coring system, which will accelerate the drilling procedure and allow the deployment of logging tools for in-hole data logging. Further plans include the development of a pressure core barrel for the recovery of sediments enriched in gas under *in situ* pressure conditions, as well as the development of sensor strings to be deployed with the MeBo for long-term monitoring of hydraulic processes and heat flow in the sea floor.

Acknowledgements

The development of the MeBo was funded by the German Federal Ministry of Education and Research and by the State Government of Bremen. The technicians and engineers at the Marum Center and cooperating companies accomplished an extraordinary performance in getting the MeBo-system running within a short development time. We thank the Leitstelle Meteor/Merian and the Irish Marine Institute for their expedition support and the crews of *R/V Meteor, R/V Celtic Explorer* and *R/V Maria S. Merian* for their support during the various deployments of the MeBo. The German Research Foundation (DFG) and the DFG Research Center Ocean Margins (RCOM) supported MeBo-cruises M65/3, CE0511, and MSM04/4. We thank the Irish Shelf Petrol Studies Group of the Irish Petroleum Infrastructure Programme Group 4 (comprising Chevron Upstream Europe, ENI *Irelandd* BV, Island Oil & Gas plc, Lundin Exploration BV,, Providene Resources plc, Ramco Energy plc, Shell E&P Ireland Ltd, Statoil Exploration (Ireland) Ltd, Total E&P UK plc and the Petroleum Affairs Division of the Department of Communications, Marine and Natural Resources) for their faith in the MeBo system, for being the first scientific user of the MeBo, and for financing its deployment on the Porcupine Bank (CE0619).

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Related Web Link

http://www.rcom.marum.de/English/Sea_floor_drill_rig_MeBo.html

InnovaRig – The New Scientific Land Drilling Facility

by Lothar Wohlgemuth, Ulrich Harms, and Jürgen Binder

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Introduction

Deep drilling is becoming an increasingly important tool to study fundamental processes at depth, such as earthquake nucleation in fault zones or volcanic structures and eruption mechanisms or other basic Earth science research topics. At the same time, there are growing demands for new sustainable energy sources (e.g., geothermal energy) and for underground storage of carbon dioxide. Drilling for such missions often takes place in unexplored, structurally or geotechnically difficult environments that require special drilling, coring, and testing capabilities. Furthermore, continuous coring, deviated drilling, and complex testing are frequently required within these kinds of research projects. However, the worldwide market for drilling devices appropriate for this is small and currently is stressed by very high hydrocarbon exploration activity. Accordingly, scientific projects are often unable to contract the right drilling rig and service, or cannot get it for the planned timeframe or at an affordable price.

Several projects in the framework of the International Continental Scientific Drilling Program (ICDP) were severely hampered by the fact that suitable rigs were not available or that they did not have the capability or the flexibility for various drilling, coring, or testing options necessary for scientific operations. For ICDP and other projects the GeoForschungsZentrum Potsdam therefore developed a new deep drilling and coring installation in cooperation with the company Herrenknecht GmbH in Schwanau (southern Germany). On 14 May 2007 the novel deep drilling and coring installation called InnovaRig was officially commissioned for a first operations test at the manufacturer's workshop (Fig. 1). From summer 2007 on, drilling of up to 5 km (~16,000 ft) depth can be realized through the derrick with a hook load of 3500 kN. One of the key features for scientific drilling in InnovaRig is that it allows for fast changes from rotary drilling to wireline diamond coring or vice versa in order to sample key lithologies and switch to faster and inexpensive rotary drilling in less important geological sections.

The Helmholtz Association of German Research Centers funded the development of the facility that is owned by the GFZ and will be made available for scientific and industrial projects through a commercial operator (Geoforschungsboh rgesellschaft). The contractual basis for this arrangement is designed to allow for industry missions during pauses between scientific drilling projects, thus avoiding costly standstill (or a need for permanent scientifically funded operations). For this reason the InnovaRig has been designed to be technologically and economically attractive for industry purposes as well. For scientific drilling projects, the day rates charged will not include depreciation of investment costs.

Technical Characteristics

In the InnovaRig, the usual standard of a rope hoist carrying the drillstring or casings is replaced by a hydraulic cylinder drawworks with 22 m stroke. Drill pipe is handled using "hand-off technologies" with semi-automated connection of two pipes to one stand in a horizontal position in a bridge magazine outside the derrick, while a new type of pipe handler transports stands into the tower from a horizontal magnetic pipe racking system on ground. The pipe handler provides practically unlimited capacity and does not compromise working on the rig floor due to setback areas. All kinds of pipe and casing in sizes between 2 ⅞" and 24½" can be handled in the system with tripping speeds of up to 500 m h^{-1}. The drillstring is driven by two separate top-drive

Figure 1. InnovaRig with hydraulic pipe handling unit on lower right side. Photo by Herrenknecht Vertical.

systems with a broad range of rotary speeds and an auxiliary rotary table. Furthermore, the mud system, tanks, and pumps are constructed to be flexible for adapting to the various drilling procedures. The complete system including rig with pipe handler, pumps, mud tanks and other equipment can be skidded for easy relocation during multiple well operations.

The design and construction of the complete InnovaRig were performed to achieve a maximum potential for fast, inexpensive operations without any negative effects on efficiency, safety, and the environment. Key features (see Table 1 for details) are:

- the modular set-up and complete containerization which allow rapid conversion, mobilization, and skidding,
- the ability to rapidly switch between various drilling options including airlift drilling in large diameters (0–500 m depths), standard rotary drilling, continuous wireline diamond drilling, casing drilling as well as underbalanced drilling,
- the high degree of automation, in particular the semi-automatic pipe-handling for safe operations, condensed rig workload, and a minimum staffing,
- the high integration of devices for scientific measurements and tests to allow for a very fast switch from drilling to science operations,
- the minimization of area required for the drill site and the project-dependent use of rig modules, and
- the option to use either public or rig-installed power sources.

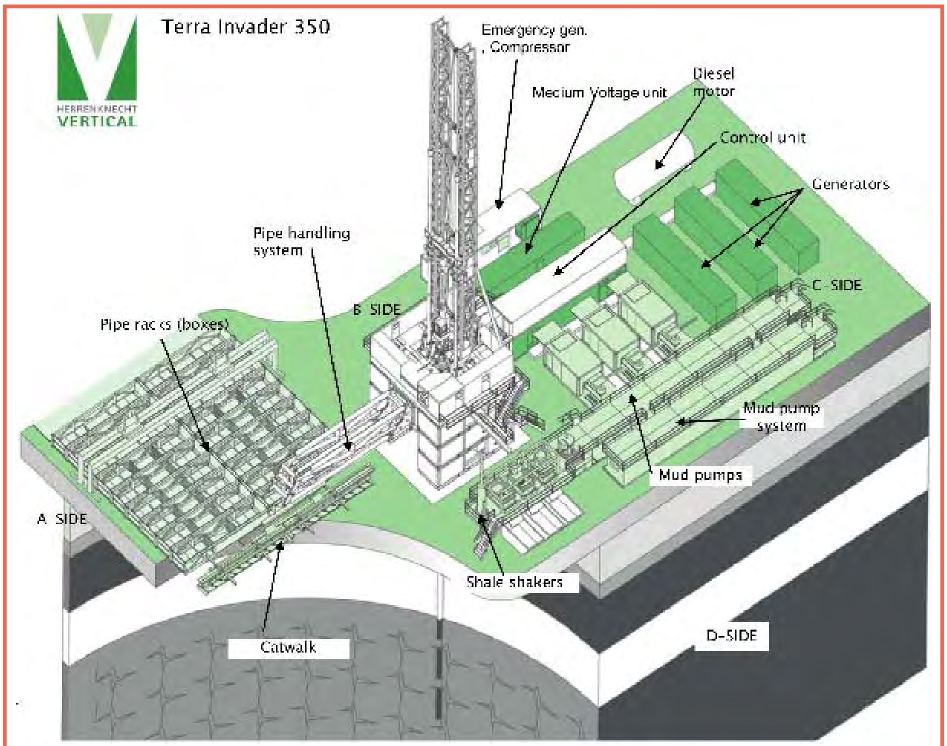

Figure 2. Sketch of the complete InnovaRig installation with derrick (center), pipe racks (left) and pumps and mud system (right). Sketch by Herrenknecht Vertical.

In terms of energy consumption and environment protection, InnovaRig can be operated through internal and/or public power supply, with biodegradable mud additives and greases. The rig is fully shielded against noise to allow deployments close to housing areas and will be extended for almost “waste-free” operations. In addition to standard equipment for rotary drilling such as 6.5-km drillstring and heavy pipes, the facility is outfitted with 5.5-km wireline pipes plus coring system and winch, 1000-m pipes for airlift drilling, as well as a 10,000 psi blowout preventer. In the case of low diameter wireline drilling in mining dimensions, the mud flow system can be easily rescaled to the volume of the circulating drilling fluid.

An important restriction is that although the rig can be partly downsized, it is a really heavy piece of equipment (Figs. 1 and 2) whose mobilization costs for more than 60 truckloads and day rates will not be suitable for shallow borings to less than ~2 km depth.

Special Installations for Science Operations

Geophysical wireline logging tools need to be deployed in research wells on short notice without lengthy backfitting. Accordingly, InnovaRig has cable guidance, sonde racks, spaces for winches, etc. integrated and in easy reach. At any time during drilling, the working platform is clear for setting up and recording wireline logs or conducting experiments such as vertical seismic profiling.

To allow a regular automatic sampling of drill chips, a sampling facility for cuttings and drill mud is provided at the mud cleaning line. This is extremely useful during non-coring phases to determine a couple of important parameters of the drilled rock column. In addition, mud samples can also be used to determine formation fluid inflow zones at depth which change the ion load in the drilling fluid. A mud gas extraction unit is also integrated to assure air contamination-free analysis of gaseous components from drilled rocks in the mud. Tracers or reference gases can be injected into the well during drilling operations through extra pipes flanged to the injection pumps. Such devices can, for example, be used to determine the lag time of the mud circulation and thereby detect the location of inflows.

Table 1. InnovaRig technical data

MAST		**HOIST**	
Height	51.8 m	Type	Hydraulic double-cylinder system
Hook load	3,500 kN (regular)	Stroke	22 m
		Power	2,000 kW
SUBSTRUCTRUE		**ROTARY TABLE**	
Type	box-on-box	Bore	953 mm
Height	9 m rig floor (9 x 10m dimension)	Nominal load	4,450 kN
Casing load	3,500 kN	Dynamic load	3,500 kN
BOP trolleys	2 x 250 kN	Drive	hydraulic (max. 200 min-1, 600 kW)
ROTARY TOP DRIVE		**CORING TOP DRIVE**	
Nominal load	4,450 kN	Nominal load	1,500 kN
Power	800 kW	Power	350 kW
Max. dyn. torque	48,000 Nm	Max. dyn. torque	12,000 kN
Max. RPM	220 min^{-1}	Max. RPM	500 min^{-1}
HYDRAULIC ROUGHNECK		**MUD PUMPS**	
Max. diameter	254 mm frame 1	Type	Electric (2 + 1 opt.)
Max. torque	508 mm frame 2	Power	1,300 kW
Max. load	4,540 kN	Max. pressure	350 bar
		Max. flowrate	2,200 L min^{-1}
ELEVATORS		**ROTARY TONGS**	
Max. diameter	254 mm frame 1	Type	Hydraulic clamping
Max. diameter	508 mm frame 2	Diameter range	73 mm–508 mm
Max. load	4,540 kN		
PIPE HANDLER		**MAGNETIC PIPE RACKING SYSTEM**	
Drive	hydraulic	Type	Horizontal
Max. diameter	620 mm	Drive	Electric
Min. diameter	73 mm	Nominal load	45,000 N per magnet group
Lifting capacity	45,000 N		

Science containers, such as a core and cuttings lab, a microbiology unit, or a containerized geochemistry lab, have extra space with power, water, and communication hook-up reserved within the setup of the drill site. The integrated data acquisition system records rig parameters, drilling data, and scientific data according to project needs. All these data are captured through a central bus system and stored in the systems main computer that offers direct connections to other data banks and Internet, and it is capable of handing over all data directly to the ICDP's Drilling Information System, DIS (Conze et al., 2007).

Outlook

The implementation of the idea to produce and operate a novel "science-owned" type of deep land drilling facility is a new pathway in scientific drilling, since land drilling endeavors are usually performed with contracted service rigs of opportunity. However, the lack (or at best, the very high costs) of suitable tools on the world market advanced this development. As it is anticipated that there will be no continuous science operations for this tool, neither within ICDP nor in other research-related drilling projects, InnovaRig will be operated on an as-needed basis also for industry. Scientific projects will have priorities, but commercial missions will be performed as long as no research project is being conducted.

Due to its outstanding, novel capabilities, InnovaRig can be used now in a very broad range of deep drilling missions for research and in industry projects. In terms of engineering, the facility is expected to establish a modern, inexpensive standard with hydraulic drive and pipe handling, as well as variable drilling capabilities. For science, the tool will provide the long-needed flexibility for coring, whenever necessary and useful, convenient installations for research without costly conversions. For these reasons, InnovaRig will support advancing Earth sciences with drilling projects.

The first deployment will be performed during this summer for a commercial 4-km-deep geothermal drilling project in southern Germany. Further applications are not yet contracted, but negotiations for the use in ICDP and in further geothermal research projects are currently underway. Proposals for the use of the InnovaRig are welcome.

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Related Web Links

www.icdp-online.org
www.vertical-herrenknecht.de

The COral-REef Front (COREF) Project

by Yasufumi Iryu, Hiroki Matsuda, Hideaki Machiyama, Werner E. Piller, Terrance M. Quinn, and Maria Mutti

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Introduction

The First International Workshop on the COral-REef Front (COREF) project was held on 14–19 January 2007 in Okinawa-jima, southwestern Japan to discuss objectives, required laboratory analyses and techniques, potential drilling sites, and scientific proposals for the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP). This article briefly introduces the project and reports the outcome of the First International Workshop on the COREF Project.

COREF Project

The COREF Project (Iryu et al., 2006) involves ocean and land scientific drilling into Quaternary reef deposits in different settings in the Ryukyu Islands (Fig. 1). Major scientific objectives are to examine the following questions:

(1) What are the nature, magnitude, and driving mechanisms of coral-reef front migration in the Ryukyus?

(2) What is the ecosystem response of coral reefs in the Ryukyus to Quaternary climate changes?

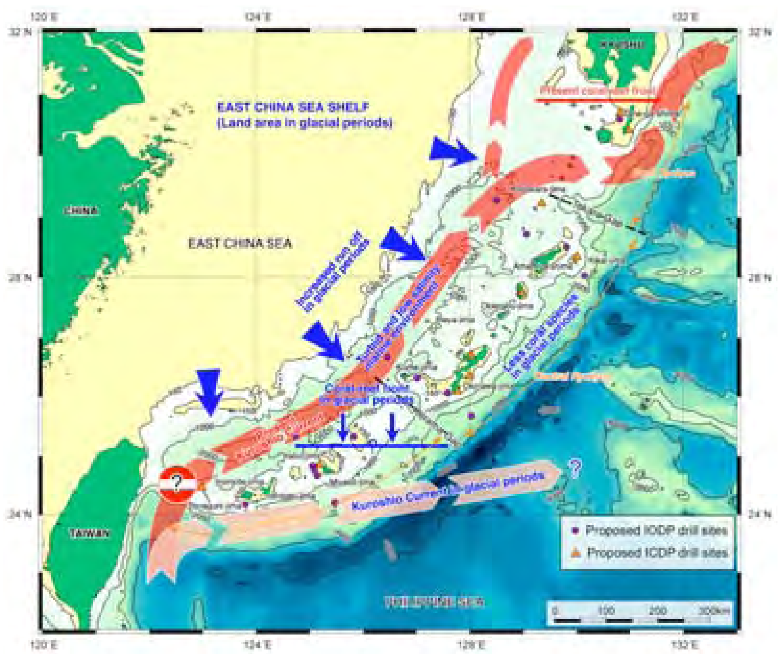

Figure 1. Modern oceanographic setting and presumed paleoceanographic conditions during glacial periods (lowstand periods) in the Ryukyu Islands. Proposed locations for land-based and off-shore drill sites are shown.

(3) What is the role of coral reefs in the global carbon cycle?

To clarify the stratigraphic succession and lithofacies distribution, it is crucial to sample both highstand and lowstand reefs currently ranging from ~200 m above sea level on the islands to ≥150 m in elevation below sea level on the shelf and shelf slope. To obtain complete stratigraphic coverage, land drilling will need to be combined with ocean drilling.

Secondary objectives include (i) the timing and causes of coral-reef initiation in the Ryukyus, (ii) the position of the Kuroshio Current during glacial periods and its effects on coral-reef formation, and (iii) early carbonate diagenetic responses as a function of compounded variations in climate, eustacy, and depositional mineralogies (subtropical aragonitic to warm-temperate calcitic).

Workshop

Participating in the workshop were a total of twenty-four scientists from seven countries/areas (Austria, French Polynesia, Germany, Japan, Korea, Taiwan, U.S.A.) representing multidisciplinary fields.

During the first day, a field excursion to an Upper Miocene to Pliocene siliciclastic slope to forearc basin deposits (Shimajiri Group), Pleistocene coral-reef carbonates (Ryukyu Group), and transitional lithofacies (Chinen Formation) illustrated the paleoceanographic transition from the "mud sea" to the "coral sea" (Fig. 2). During the following three days, the geologic setting of the Ryukyu Islands and the stratigraphic scheme of the Plio-Pleistocene carbonate succession were presented in detail, and existing datasets relevant to the COREF Project were reviewed at the Global Oceanographic Data Center of the Japan Agency for Marine-Earth Science and Technology (GODAC/JAMSTEC; http://www.godac.jp/top/en/index.html). Discussions also addressed the regional geologic framework, the availability of biota (corals and foraminifers), diagenetic features as paleoenvironmental proxies, and critical issues related to age determination of the carbonate sequences.

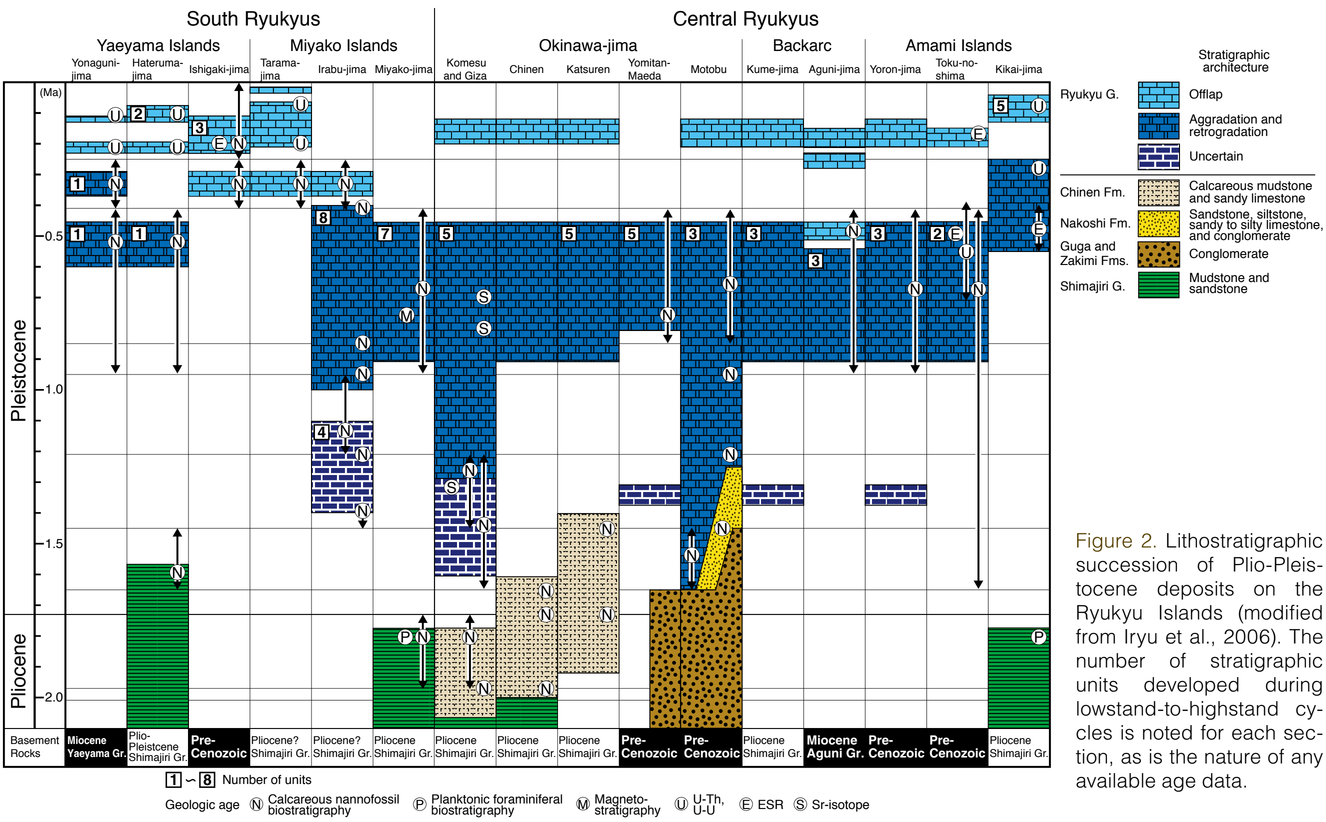

Figure 2. Lithostratigraphic succession of Plio-Pleistocene deposits on the Ryukyu Islands (modified from Iryu et al., 2006). The number of stratigraphic units developed during lowstand-to-highstand cycles is noted for each section, as is the nature of any available age data.

Finally, the workshop participants selected potential drill sites for the COREF Project (Fig. 1).

Major Issues

Drilling sites: The workshop selected drill sites on transects along and across the Ryukyu Island Arc. The northeast-southwest transect along the Ryukyu Island Arc extends from 24°N (south Iriomote-jima) to 31°N (west of Tane-ga-shima), covering islands from subtropical to warm-temperate regions (Fig. 1). The northernmost site is located on the northern limit of the modern coral-reef formation. At present, the distance between areas characterized by reefal coral communities and those by non-reefal coral communities (midway between Amami-o-shima Island and Tane-ga-shima Island; Fig. 1) is approximately 150 km (for definitions of reefal/non-reefal coral communities, see Veron, 1995). Therefore, the drilling sites on the northeast-southwest transect were designed to be located within an interval <200 km. Drilling on this transect will provide information on the nature and magnitude of coral-reef front migrations between glacial and interglacial periods. The northwest-southeast transects across the Ryukyu Island Arc are located near Amami-o-shima, Okinawa-jima, and Miyako Islands. These drilling sites are located from proximal (reef) via distal (off-reef) parts of ancient carbonate factories to shelf slopes toward the Okinawa Trough and the Ryukyu Trench. These drilling transects will recover a complete stratigraphic succession of the Quaternary carbonate deposits in the Ryukyus at different latitudes.

Coral-reef ecosystem: In the South and Central Ryukyus, corals build extensive fringing reefs dominated by a highly diverse assemblage of acroporid and poritid corals (Sugihara et al., 2003). Conversely, reefs at Tane-ga-shima, near the northern limit of coral-reef distribution, are thin, narrow, sparsely distributed, and dominated by only a few high-latitude coral species (Ikeda et al., 2006). North of the reef front, coral communities are dominated by faviid corals as well as a few other species. The latter are particularly abundant at high latitudes or even endemic to mainland Japan and commonly form large monospecific stands (Japanese Coral Reef Society and Ministry of the Environment, 2004). The compositions of larger foraminiferal assemblages in the North Ryukyus are distinguished from those found in the South and Central Ryukyus by the disappearance of *Calcarina gaudichaudii* and *C. hispida* (Sugihara et al., 2006). Nongeniculate coralline algae constitute the third taxonomic key-group emphasized during the workshop, because of their potential use as depth indicators in the fossil record (Iryu, 1992).

Workshop participants stressed the importance of establishing a schematic diagram summarizing the distribution of corals, benthic foraminifers, and coralline algae as a function of bathymetry, irradiance, water energy, and latitude (north and south of the reef front).

Age control: As the main body of the Pleistocene reef and off-reef deposits formed in the Ryukyus before 0.3 Ma (Fig. 2), they are beyond the limit of the $^{230}Th/^{234}U$ dating method. Thus, biostratigraphy, strontium (Sr) isotope stratigraphy, and magnetostratigraphy are the three principal techniques providing chronostratigraphic constraints to carbonate sequences to be recovered during the COREF Project.

Calcareous nannofossil biostratigraphy provides a good chronological constraint to shallow water carbonates (Yamamoto et al., 2006). However, two major problems exist– 1) although a high abundance of nannofossils within mixed siliciclastic and carbonate sediments is expected, few fossils may be found from well-indurated and diagenetically altered carbonate rocks, and 2) time resolution of calcareous nannofossil biostratigraphy (twelve datum plains in the Quaternary sequence) is hardly sufficient to resolve the effect on coral reefs of Quaternary glacio-eustatic sea level oscillations. However, precise dating by Sr isotope stratigraphy is possible for shallow water carbonates older than 1 Ma and free of siliciclastic grains/clasts. Magnetostratigraphy is a powerful tool for precise temporal correlation and accurate dating of sediments, even for recrystallized and dolomitized carbonates; however, there are few references on magnetostratigraphic dating and rock magnetic characterization of the Pleistocene carbonate sequences in the Ryukyus. Sakai and Jige (2006) showed that bacterial magnetite minerals in the deposits carry an original depositional remanent magnetization useful for magnetostratigraphic dating.

Multiple techniques, such as electron spin resonance (ESR) and thermoluminescence dating methods, will therefore need to be used to date the samples of the COREF Project.

Towards the Achievement of the COREF Project

The workshop participants agreed that both land and offshore drilling is required to address the scientific objectives of COREF and that proposals should be submitted to IODP and ICDP for such drilling. A thorough data mining of the literature on the Pleistocene carbonates and their basement rocks, especially Cenozoic sequences in the Ryukyus, is needed because most works were published in local journals with limited distribution. The proponent group welcomes geochemists studying thermoluminescence and ESR dating methods to join the project team.

Acknowledgements

This workshop was jointly funded by the ICDP and the Japan Drilling Earth Science Consortium (J-DESC). Meeting room and facilities were provided by GODAC/JAMSTEC.

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Related Web Links

http://www.godac.jp/top/en/index.html
http://www.dges.tohoku.ac.jp/igps/iryu/COREF/
http://coref.icdp-online.org/

Upcoming Workshops

Colorado Plateau Coring Workshop 2007

13–16 Nov. 2007, St. George, Utah, U.S.A.

The Colorado Plateau is the textbook example of layered sedimentary rocks in North America, representing the depositional history of the western Cordillera during much of the Paleozoic and Mesozoic. A focused coring program in Triassic through Lower Jurassic strata on and east of the Colorado Plateau would result in a quantum leap in our insight into issues of Pangean chronology, paleogeography, paleoclimate, and biotic evolution that also include those associated with the Triassic-Jurassic boundary. Topics include how the transition from the Paleozoic to a modern terrestrial ecosystems took place, how largely fluvial systems respond to cyclical climate, what the global or regional climate trends vs. plate position changes in "hot house" Pangea were, and how the major tectonic and eustatic events of the time were recorded in low accommodation continental settings.

The workshop is sponsored by DOSECC and NSF. More information and registration are at http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page.html.

12th Ann. Continental Scientific Drilling WS

June 2008, Moab, Utah, U.S.A. Application deadline: 15 April 2008

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

Limited funding is available for travel. Members of the scientific community who wish to contribute or participate in the workshop are invited to submit an application. The workshop details will be posted in early 2008 on DOSECC's website: http://www.dosecc.org. For more information contact David Zur (dzur@dosecc.org).

ICDP Workshop to Investigate Hominin-Paleoenvironmental History

Unconfirmed date and venue: late 2008, Nairobi, Kenya.

This workshop will consider the scientific opportunities and technical challenges of obtaining sediment cores from several of the most important fossil hominin and early Paleolithic artifact sites in the world, located in Kenya and Ethiopia. The objective will be to drill in near-continuous sedimentary sequences close to areas of critical importance for understanding hominin phylogeny, covering key time intervals for addressing questions about the role of environmental forcing in shaping human evolution. These sites are all currently on land, but consist of thick lacustrine sedimentary sequences with rapid deposition rates. Therefore, the proposed sites combine the attributes of relatively low-cost targets (in comparison with open water, deep lake sites) and the potential for highly continuous and informative paleoenvironmental records obtainable from lake beds.

Info will be available at http://magadi.icdp-online.org.

The Thrill to Drill: Continental Scientific Drilling Townhall Meeting

10 December 2007, San Francisco, California, U.S.A.

As previous years, DOSECC and ICDP will host a townhall meeting at the Fall AGU 2007 in San Francisco. Feel free to drop in to meet people and learn and chat about the drilling programs. Time and date await confirmation, so visit http://www.dosecc.org or http://www.icdp-online.org for the latest information. We look forward to welcoming you in San Francisco!

Multidisc. Observatory & Laboratory of Experiments Along a Drilling in Central Italy

Spring 2008, Central Italy.

The workshop will prepare a drilling project to investigate the shallow crust and the inner structure of normal faults in Northern Apennines to study geophysical and geochemical processes controlling normal faulting and earthquake ruptures during moderate-to-large seismic events as well as the low angle normal fault paradox. The sites in the Umbria-Marche sector of Northern Apennines offer a unique opportunity to reach a complex system of anthitetic normal faults: an active fault dipping SW at 40°–45°, which ruptured during a recent earthquake sequence in 1997 (Colfiorito fault) and a low angle normal fault dipping 15°–25° towards ENE (Alto Tiberina Fault).

More info available from http://apennines.icdp-online.org.

Testing Extensional Detachment Paradigm in the Sevier Desert Basin (Western U.S.)

Tentative date and venue: 15–18 July 2008, Salt Lake City, Utah, U.S.A.

Low-angle normal faults or detachments are widely regarded as playing an important role in crustal extension and the development of passive continental margins. No consensus exists on how to resolve the mechanical paradox implied or to account for the general absence of evidence for seismicity. Drilling to a depth of 2–4 km in the Sevier Desert basin of west-central Utah will test the extensional detachment paradigm through coring, downhole logging, biostratigraphic, isotopic and fission-track dating, magnetostratigraphy, and *in situ* measurement of pore pressure, permeability, fluid chemistry, temperature and stress orientation/magnitude.

More info at: http://www.ldeo.columbia.edu/sevier/icdp/.

DSDP and ODP Legacy Publications Online

Published volumes detailing nearly 40 years of scientific discoveries from ocean drilling research are now freely accessible online. All findings and data published in the Ocean Drilling Program (ODP) and the Deep Sea Drilling Project (DSDP) pulication series and program reports are online. ODP publications are available at http://www.odplegacy.org (click on Samples, data & publications). DSDP publications are available at http://www.deep-seadrilling.org.

The *Proceedings of the Ocean Drilling Program* includes an *Initial Reports* volume of shipboard reports for each ODP research cruise and a companion *Scientific Results* volume of peer-reviewed postcruise research results. ODP first began publishing its *Proceedings* online in 1997. Through the digitization effort, scanned versions of ODP *Proceedings* volumes originally published between 1986 and 1996 have been made Web-accessible.

The HTML tables of contents provide navigation to individual chapter files. PDF chapter files generated from more than 185,000 pages through the digitization project started as scanned images of each original page. Through the use of optical character recognition (OCR), a searchable text layer was added, allowing the user to copy and paste text from the final PDF files. The digitized volumes include links to individual core photographs scanned from original film as part of a separate ODP legacy project.

Every chapter in both the *Proceedings of the Ocean Drilling Program* and the *Initial Reports of the Deep Sea Drilling Project* has a digital object identifier (DOI) associated with it. With information about DSDP and ODP publications deposited with the DOI, publishers can now link directly online to cited papers across the DSDP and ODP series.

The digitization project was carried out at the Texas A&M University Digital Library in a joint venture with ODP sponsored by the U.S. National Science Foundation.

ODP was a 20-year international partnership of scientists and research institutions organized to explore the evolution and structure of the Earth through scientific ocean drilling. It conducted drilling operations in the world's oceans from January 1985 through September 2003. The program succeeded DSDP, which began drilling operations in 1968 and concluded its explorations in 1983. The Integrated Ocean Drilling Program (IODP) has been building upon the legacy of success of both its predecessor programs since 2004.

Conversion of the *JOIDES Resolution* Progressing

Joint Oceanographic Institutions (JOI) announced in April 2007 that Overseas Drilling Limited has signed a contract with Jurong Shipyard PTE LTD for the overhaul and enhancement of the research vessel *JOIDES Resolution*. The shipyard contract covers work through 2007, when the vessel is to be delivered for sea trials before returning to service for the Integrated Ocean Drilling Program (IODP) in 2008.

There have been great efforts by NSF and the USIO to keep the Scientific Ocean Drilling Vessel (SODV) project moving forward, despite severe cost pressures. As of July 2007 purchase of new science equipment was nearly complete, refurbishment of some existing equipment continued, and land based testing and integration had begun. Many ship and drilling service life extension projects have been completed and others are continuing. The drilling equipment, including the drilling derrick, were removed from the ship and refurbishment is well underway (see photos). To prepare the ship for new science facilities and accommodations, demolition of the existing facilities was required. To that end the lab stack, lifeboats, davits, and bridge have been removed and the accommodations have been gutted. Operations are scheduled to begin in 2008.

Since 2004 the *JOIDES Resolution* has been the U.S. platform for the IODP. For the majority of the previous two decades, the ship was employed by the

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AAAS—14–18 Feb. 2008, Boston, Mass., U.S.A.
AAPG—20–23 Apr. 2008, San Antonio, Tex., U.S.A.
OTC—5–8 May 2008, Houston, Tex., U.S.A.
EGU—13–18 Apr. 2008, Vienna, Austria
JPGU—May 2008, Chiba, Japan
IGC—6–14 Aug. 2008, Oslo, Norway

**Conference exhibitions may be added or changed. Visit http://www.iodp.org for calendar updates.*

Ocean Drilling Program, predecessor to the IODP. For the latest information and more spectacular pictures about the SODV project visit http://joiscience.org/sodv/.

IODP Phase 2 Started

With the start of the first expedition of the NanTroSEIZE project in October 2007, the second phase of IODP has begun. During IODP Expedition 314 the Japanese drilling vessel *Chikyu* will drill a subduction zone off southern Japan. The first phase of IODP spanned from 2004 to 2005, comprising operation of twelve research expeditions. Ten expeditions were undertaken by the riserless U.S. operated drilling vessel *JOIDES Resolution* and two expeditions were performed by mission-specific platforms operated by the European Consortium for Ocean Research Drilling (ECORD). After a drilling hiatus of almost two years the IODP's options are now enhanced by the use of the *D/V Chikyu*, a ship providing riser drilling technology supplied to the program by the Japan Agency for Marine Earth-Science and Technology. In addition the U.S. ship *JOIDES Resolution* is being significantly remodeled, enhanced and upgraded, which will allow scientists to address new and previously inaccessible drilling targets.

In preparation for the upcoming expeditions, the first *Scientific Prospectuses* for Expeditions 314–316 have been published and made available on the Web (http://www.iodp.org/scientific-publications/). Applications for upcoming expeditions can be submitted through IODP's Web page at http://www.iodp.org/apply-to-sail/.

ICDP Training Course 2007

Each year the ICDP conducts a one-week field course to train scientists and engineers on basics in scientific drilling. The key aspects of the courses cover project planning and management, drilling technology, borehole measurements, scientific on-site analyses, and information management. The training is open for advanced students, PhD students, post-docs from ICDP member countries and is recommended for managers and scientists from forthcoming ICDP projects.

The training will be held in Windischeschenbach, Germany, the drill site of the scientific deep drilling project KTB, from 5–9 November this year. A highlight will be an excursion to InnovaRig, the newly developed facility for scientific drilling (see Wohlgemuth et al., this issue). The detailed program can be found in "News>>Upcoming Events" on the ICDP webpage: http://www.icdp-online.org.

First Results of ICDP Bosumtwi Project Published

The first results of the impact and geophysical aspects of the ICDP drilling project have just been published in a special double issue (April–May 2007) of the international journal Meteoritics and Planetary Science. See http://www.ingentaconnect.com/content/arizona/maps for contents and abstracts. As a service to the ICDP community, these 27 articles have also been placed online at the ICDP Bosumtwi Web site under "references", see http://www.icdp-online.org/contenido/icdp/front_content.php?idcat=446. More work, especially also on the lake sediments as well as impactites, is in progress.

ICDP welcomes new members Italy and Spain

Italy and Spain have recently completed Memoranda of Understanding on membership and participation in the International Continental Scientific Drilling Program (ICDP). A Consortium of the Instituto Nazionale di Geofisika e Vulcanologica (INGV) and Centro Regionale di Competenza Analisi e Monitoraggio del Rischio Ambientale CRdC (AMRA) are partners in ICDP for Italy while the Spanish Ministry of Education and Science joined in for the Spanish Earth science community.

ESSAC Office in Aix-en-Provence after 1 Oct. 2007

After two efficient and fruitful years in Cardiff, U.K., the ESSAC office rotates to Aix-en-Provence in France on 1 October 2007. It will be located at CEREGE, Europôle Méditerranéen de l'Arbois, BP80, 13545 Aix-en-Provence cedex 4, France. Gilbert Camoin (gcamoin@cerege.fr) will take over from Chris MacLeod to serve as the new ESSAC Chair. The new ESSAC Science Coordinator is Bonnie Wolff-Boenish, who was previously Program Manager of the German Priority Program (PP) International Continental Scientific Drilling Program (ICDP) at the University of Potsdam since 2005.

Scientific Drilling Special Issue on Fault Zones

Scientific Drilling will print its first special issue in October 2007 on the results of the Fault Zone Workshop held in May 2006 in Miyazaki, Japan. This issue will contain the white paper as the result of the workshop, as well as selected abstracts from the presentations given. The editorial board consists of the workshop steering committee: Harold Tobin, Steve Hickman, Jan Behrmann, Hisao Ito, and Gaku Kimura. Since only a limited number of copies will be printed, it will not be distributed like the regular issues of *Scientific Drilling*. Interested scientists or libraries are welcome to send an email with their mailing address to journal@iodp-mi-sapporo.org to request a printed copy. Requests are served as long as supplies last. The special issue on the Fault Zone Workshop will also be available online in PDF format from http://www.iodp.org/scientific-drilling/.

Schedules

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

	ESO Operations	Platform	Dates	Port of Origin
1	New Jersey Shallow Shelf	MSP	TBD	TBD
	USIO Operations	**Platform**	**Dates**	**Port of Origin**
2	Equatorial Pacific Transect I	*JOIDES Resolution*	May–July '08	
3	Bering Sea	*JOIDES Resolution*	July–Sept. '08	
2	Equatorial Pacific Transect II	*JOIDES Resolution*	Sept.–Nov. '08	
4	Canterbury	*JOIDES Resolution*	Nov. '08–Jan. '09	
5	Wilkes Land	*JOIDES Resolution*	Jan.–Mar. '09	
	CDEX Operations	**Platform**	**Dates**	**Port of Origin**
6	NanTroSEIZE - LWD Transect	*Chikyu*	21 Sep.–16 Nov. '07	Shingu, Wakayama, Japan
6	NanTroSEIZE - Mega-Splay Riser Pilot	*Chikyu*	16 Nov.–19 Dec. '07	
6	NanTroSEIZE - Thrust Faults	*Chikyu*	19 Dec. '07–05 Feb. '08	
	Maintenance	*Chikyu*	Mar.–May '08	

MSP = Mission Specific Platform TBD = to be determined

All dates are approximate. Schedule is subject to approval by NSF/MEXT.

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

	ICDP Projects	Drilling Dates	Location
1	Fennoscandian Arctic Russia-Drilling Early Earth Project	May–Nov. '07	Kola, Russia
2	San Andreas Fault Zone Observatory at Depth	Jun. '02–Oct. '07 *	Parkfield, Calif., U.S.A.
3	Iceland Deep Drilling Project	sched. for '07–'10	Krafla, Iceland
4	Lake El'gygytgyn Drilling Project	sched.for '08–'10	Chukotka, Russia
5	New Jersey Continental Shelf **	sched. for summer '08	Offshore New Jersey, U.S.A.
6	PASADO (Lake Potrak Aike)	sched. for fall '08	Patagonia, Argentina
7	Lake Van	sched. for summer '09	Anatolia, Turkey

* Subsequent Borehole Monitoring until 2020

** IODP-ICDP joint project