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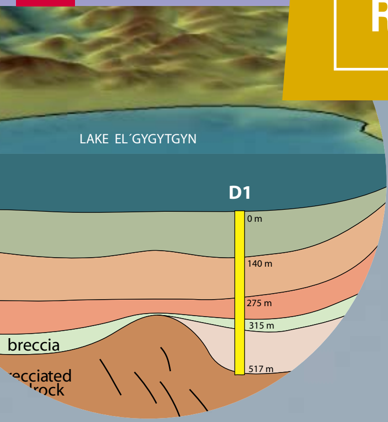
Scientific Drilling

Reports on Deep Earth Sampling and Monitoring



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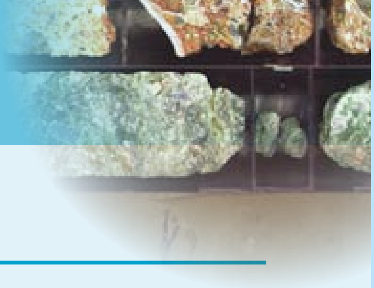
Editorial Preface



Dear Reader:

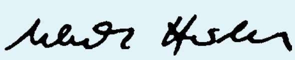
A strong Northern Hemisphere 2010 winter might have shifted attention away from the issue of climate change, but climate change is about more than just annual weather patterns. Research must focus on broader impacts, such as the effect of changes in the oceans' water masses on global climate. The refurbished ocean drilling vessel *JOIDES Resolution* (*JR*) made its 'maiden voyage' in the equatorial Pacific Ocean in 2009. This area absorbs solar radiation into a giant warm water pool and is the source of the inter-annual El Niño Southern Oscillation phenomenon (ENSO) affecting the climate of the entire circum-Pacific and beyond. A drilling transect by the *JR* from the northwestern to southeastern equatorial Pacific took advantage of lithospheric plate motion to recover high-resolution sedimentary equatorial sections from most of the Cenozoic era (p. 4); this will enable a much better understanding of the global climate control exerted by this ocean.

The *JR* proved her reputation as the workhorse of ocean drilling, providing remarkable core recovery to greater depths than ever before; results from these cores can underpin unprecedented detailed analyses of ocean and climate history. Understanding climate and sea-level change of the past is the only real benchmark test for assessing the impact of anthropogenic greenhouse gasses on the global environment. Naturally, as we prepare for a new ten-year program of scientific ocean drilling, societally important fields such as environmental changes, earthquakes and other geohazards are in focus along with principal research themes directed at the fundamental dynamic behavior of our planet. A major milestone of future science planning was achieved with the recent INVEST conference soliciting ideas from across the Earth and life science community for the scientific themes of the new program (summary report on p. 54).

Environmental change is no threat to continued life on Earth, only to the success of specific species (e.g., humans). A milestone study of the ICDP addresses the profound change of the conditions for life on Earth when the atmosphere went from oxygen-poor to oxygen-rich more than two billion years ago. These remarkable ICDP drill cores (p. 23) from western Russia throw new light on this most fundamental change in Earth's exterior environment.

So, dear reader, please take a deep breath (of oxygen) and enjoy the ride through Earth's history and how scientific drilling helps us to understand it!

Hans Christian Larsen
Editor-in-Chief



Ulrich Harms
Editor

Front Cover: ICDP drilling at the frozen El´gygytgyn (local name in Chukchi language [чукчи] meaning "White Lake") addressing past climate history at extreme northeastern Siberia and the impact of an extraterrestrial bolide that generated the 12-km-wide lake basin 3.6 Ma ago.
Left inset: Preliminary geological model of sequence drilled in the Russian Arctic.

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

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

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Contents

Science Report

Progress Reports

Technical Developments

Workshop Reports

News and Views

Schedules

The Pacific Equatorial Age Transect, IODP Expeditions 320 and 321: Building a 50-Million-Year-Long Environmental Record of the Equatorial Pacific Ocean

by Mitchell Lyle, Heiko Pälike, Hiroshi Nishi, Isabella Raffi, Kusali Gamage, Adam Klaus, and the IODP Expeditions 320/321 Scientific Party

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Introduction

In March 2009, the R/V *JOIDES Resolution* returned to operations after its extended refit and began with a drilling program ideally suited to its drilling strengths, the Pacific Equatorial Age Transect (PEAT, IODP Exp 320/321; Fig. 1A). The PEAT drilling program was developed to understand how a major oceanic region evolved over the Cenozoic Era (65–0 Ma) and how it interacted with global climate. It specifically targeted the interval between 52 Ma and 0 Ma and drilled a series of sites that originated on the paleoequator. These sites have since been moved to the northwest by plate tectonics.

The equatorial Pacific is an important target for paleoceanographic study because it is a significant 'cog' in the Earth's climate machine, representing roughly half of the total tropical oceans that in turn represent roughly half of the total global ocean area. Prior drilling in both the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) outlined the changes that have occurred through the Cenozoic (e.g., van Andel et al., 1975; Pisias et al., 1995). Not only did the earlier work fail to cover sufficient time intervals but also many of the sites were cored with 'first-generation' scientific drilling technology with incomplete and disturbed sediment recovery and thus cannot be used for detailed studies.

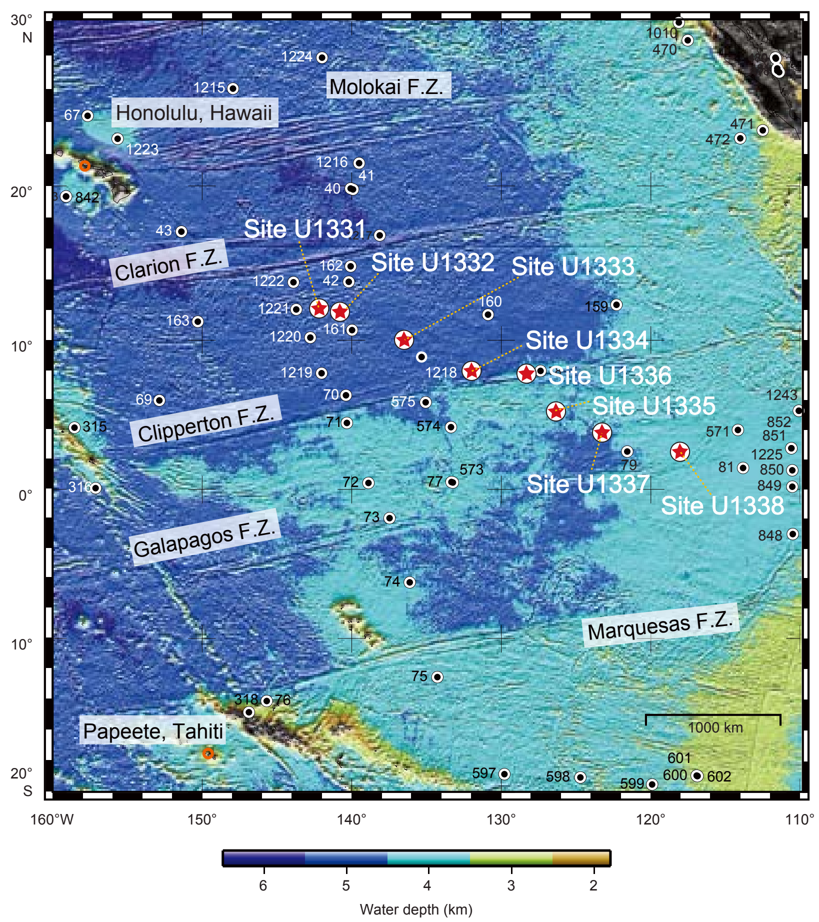

Figure 1A. Present locations of Pacific Equatorial Age Transect (PEAT) drill sites (red stars) on a bathymetric map of the central Pacific. Also shown are locations of previous DSDP and ODP drilling (solid black circles), as well as Honolulu, Hawaii and Papeete, Tahiti (open red circles). F.Z. = fraction zone.

ODP Legs 138 and 199 provide the best sample material from previous drilling, but each leg recovered sections spanning less than 10 million years suitable for cyclostratigraphy (the use of earths orbital cycles, recorded in sediments, as a measure of time). Up until the PEAT program it was difficult to achieve more than a reconnaissance of the environmental changes that have occurred in the equatorial Pacific. The PEAT program was designed to augment previous drilling and collect undisturbed sediments that could be spliced into a continuous, high-resolution environmental record of the eastern equatorial Pacific for the entire period from 56–0 Ma to present.

Why Study the Eastern Equatorial Pacific?

As the world's largest ocean, the Pacific Ocean is intricately linked to major global changes that took place during the Cenozoic. The equatorial Pacific is a major area for trapping of incoming solar radiation (Bryden and Brady, 1985), a major zone of high primary productivity (Chavez and Barber, 1987; Westberry et al., 2008), and an important region for CO_2 exchange from the deep ocean to the atmosphere (Takahashi et al., 1997).

It is also the source of one of the strongest modern inter-annual climate oscillations, the El Niño-Southern Oscillation (ENSO, Philander, 1983; Cane and Zebiak, 1985). Furthermore, previous work has shown that the equatorial Pacific west of the East Pacific Rise (~100°W) coherently responds over distances >1000 km on timescales as short as ENSO (Philander, 1983) and as long as millions of years (Mayer et al., 1986; Shackleton et al., 1995; Pälike et al., 2005). It also has been established, largely via scientific drilling, that there have been large-scale, global changes in climate over the Cenozoic that affected the equatorial Pacific (van Andel et al., 1975; Mayer et al., 1986; Pisias et al., 1995; Zachos et al., 2001a; ODP Leg 199 Shipboard Scientific Party, 2002; Zachos et al., 2008).

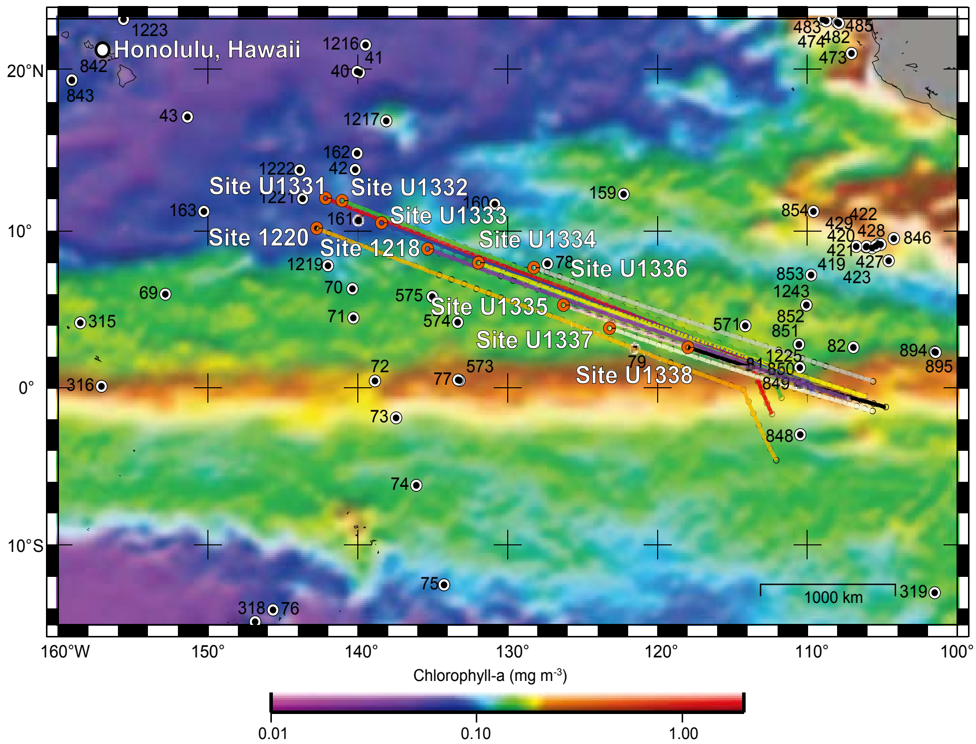

Figure 1B. Backtracked positions for PEAT sites (open red circles) , using stage poles from Koppers et al. (2001) superimposed on a satellite-derived (GlobColour) map of present ocean chlorophyll-a concentrations (December 2005 monthly mean) where red = high productivity and blue = low productivity. Solid black circles = previous DSDP and ODP sites.

The circulation of the equatorial surface ocean is inescapably linked to the trade wind system. The equatorial Pacific is the classic “world ocean” example of this linkage; it is dominated by wind-driven circulation and is largely unfettered by ocean boundaries. Here, the equator itself is characterized by a narrow zone of divergence that results from the change in the sign of the Coriolis Effect and that gives rise in the modern world to a band of high biologic productivity within a 2° latitudinal band of the equator (Fig. 1B). The strength of the equatorial circulation and of this divergence is linked to the strength of the trade winds, which are in turn strongly tied to the global climate system. Variations in global climate, inter-hemispheric differences in temperature gradients, and marked changes in the ocean boundaries are all imprinted on the biogenic-rich sediments accumulating in the equatorial zone.

Finally, the equatorial Pacific may have responded to the closing of Tethys gateways, potentially a significant Cenozoic climate driver. Closure of the Panama gateway and the constriction of the Indonesian Passage should both have affected the Pacific, and indeed, evidence for oceanographic change associated with these gateway restrictions are recorded in

PEAT Science Objectives:

1. To detail the nature and changes of the carbonate compensation depth (CCD) over the Cenozoic in the paleoequatorial Pacific
2. To determine the evolution of paleoproductivity of the equatorial Pacific over the Cenozoic
3. To validate and extend the astronomical calibration of the geological timescale for the Cenozoic, using orbitally-forced variations in sediment composition known to occur in the equatorial Pacific, and to provide a fully integrated and astronomically calibrated bio-, chemo-, and magnetostratigraphy at the equator
4. To determine temperature (sea-surface and bottom water), nutrient profiles, and upper water column gradients
5. To better constrain Pacific plate tectonic motion and better locate the Cenozoic equatorial region in plate reconstructions, primarily via paleomagnetic methods
6. To make use of the high level of correlation between tropical sedimentary sections and existing seismic stratigraphy to develop a more complete model of equatorial circulation and sedimentation
7. To provide information about rapid biological evolution and turnover rates during times of climatic stress
8. To improve our knowledge of the reorganization of water masses as a function of depth and time, as the PEAT drilling strategy also implies a paleo-depth transect
9. To develop a limited N-S transect across the paleoequator, caused by the northward offset of the proposed sites by Pacific plate motion, providing additional information about N-S hydrographic and biogeochemical gradients
10. To obtain a transect of mid-ocean-ridge basalt (MORB) samples from a fixed location in the absolute mantle reference frame, and to use a transect of basalt samples along the flowline that have been erupted in similar formation-water environments to study low-temperature alteration processes by seawater circulation

Neogene equatorial Pacific and Caribbean sediments (Keigwin, 1982; Romine and Lombari, 1985; Lyle et al., 1995; Haug and Tiedemann, 1998; Roth et al., 2000; Cane and Molnar, 2001; Lyle et al., 2008).

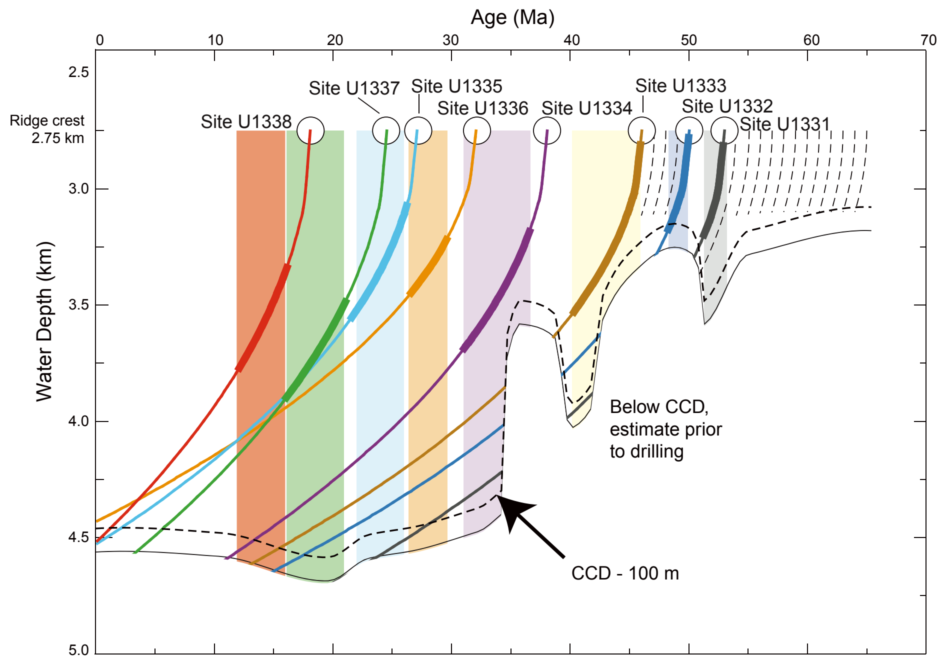

Figure 2. Targeting drill sites prior to coring based on calcium carbonate compensation depth (CCD) history (van Andel, 1975), with additional data from Leg 199. Colored boxes = critical time interval targeted for each site. Colored subsidence lines are critical time intervals where we also expected carbonate to be deposited (i.e., when site is above CCD). Subsidence curves use a subsidence parameter calculated from estimated basement age of PEAT sites and their present-day depth (k = ~0.35). Additional subsidence due to sediment loading was not modeled.

Design of the PEAT Drilling Program

The primary design criterion of PEAT drilling was to recover sediments deposited in the equatorial zone during different time slices of the Cenozoic and assemble them into an equatorial Pacific 'megasplice' covering the interval from 56 Ma to present. The sedimentary records from "off-splice" latitudes are not ignored, but they give important insight into the strength of winds, currents, upwelling, productivity, and changes in carbonate compensation depth (CCD) once the chronostratigraphy is properly calibrated (Hovan, 1995; Lyle, 2003; Moore et al., 2004). The off-equatorial sediments are also important for calibration of paleomagnetic stratigraphy with well-developed equatorial Pacific biostratigraphy (Schneider, 1995; Lanci et al., 2005). Text box on the previous page provides the scientific objectives for the PEAT program.

Tectonic motions of the Pacific plate help to make the equatorial Pacific an attractive target for recovery of environmental records. The Pacific plate has moved with a northward latitudinal component of around 0.25° m.y.$^{-1}$ for the last 43 million years, and it moved slightly faster to the north prior to that time (Koppers et al., 2001). The north-west movement of the Pacific plate transports the equatorial sediments gradually out from under the zone of highest primary productivity at the equator, resulting in a broad mound of biogenic sediments (Fig. 1B). The transport of crust away from this equatorial zone of rapid sedimentation into regions with lower sedimentation rates keeps older equatorial sediment sections from being buried deeply beneath younger sediments. However, this tectonic movement requires that a complete environmental record of the equatorial region must be spliced together from different drill sites. Assembling a complete equatorial record requires periodic shifts to new drill site locations that contain sediments of the appropriate age deposited within the equatorial zone (Fig. 1).

While the tectonic transport of each drill site complicates reconstruction, the diminished overburden resulting from transport out of the relatively fast sedimentation regime near the equator also minimizes potential burial diagenesis and allows for good preservation of biogenic sediments. In addition, because of the shallow overburden, most of the sediment column can be cored by the advanced piston coring technique to recover sediments with minimal drilling disturbance. The northward rate of tectonic displacement, however, is not so large that a traverse of the equatorial zone (within two degrees latitude of the equator) was too rapid to record a reasonable period of equatorial ocean history. Typically drill sites remain within the equatorial zone for 10–20 m.y. before passing beyond the northern edge of high biogenic sedimentation.

The Flow Line Strategy and Equatorial Carbonate Compensation Depth

The PEAT drilling program pursued a "flow line" rather than the "timeline" strategy pursued by previous ODP drilling legs for two reasons. A latitudinal transect (timeline) best resolves the structure of the equatorial current system, but for only a limited time window. Ocean crust cools and sinks as it ages, and the sea-floor on which the sediments are deposited approaches the lysocline and CCD within a few million years, especially during the Paleogene when the CCD was shallow. Thus, the best preserved part of sections recovered in such timeline transects is restricted by the depth at which carbonate dissolution significantly increases, as well as by the northward movement of sediment sections out of the region of high equatorial productivity. This limitation was exemplified by the results from ODP Leg 199, which recovered only limited amounts of carbonate prior to the Eocene/Oligocene boundary (e.g., at ODP Site 1218 on 42-Ma-aged crust; Coxall et al., 2005).

Most paleoceanographic indices are measured on carbonates, so only a few million years at a time can be studied in detail via the timeline approach. It would take too long to drill the number of timeline transects needed to complete a Cenozoic history of the equatorial Pacific. Fortunately, the coherent response of the equatorial Pacific to climate events covers vast areas, so that one site drilled near the equator can be used to understand changes over much of the region. When this flow line strategy is linked to previous drilling, a synoptic view of the Pacific can be developed. The most recent ODP Legs 199 and 138 drilled along a line of equal oceanic crustal age, thus obtaining an approximate north-south transect across the major east-west currents during time intervals of particular interest.

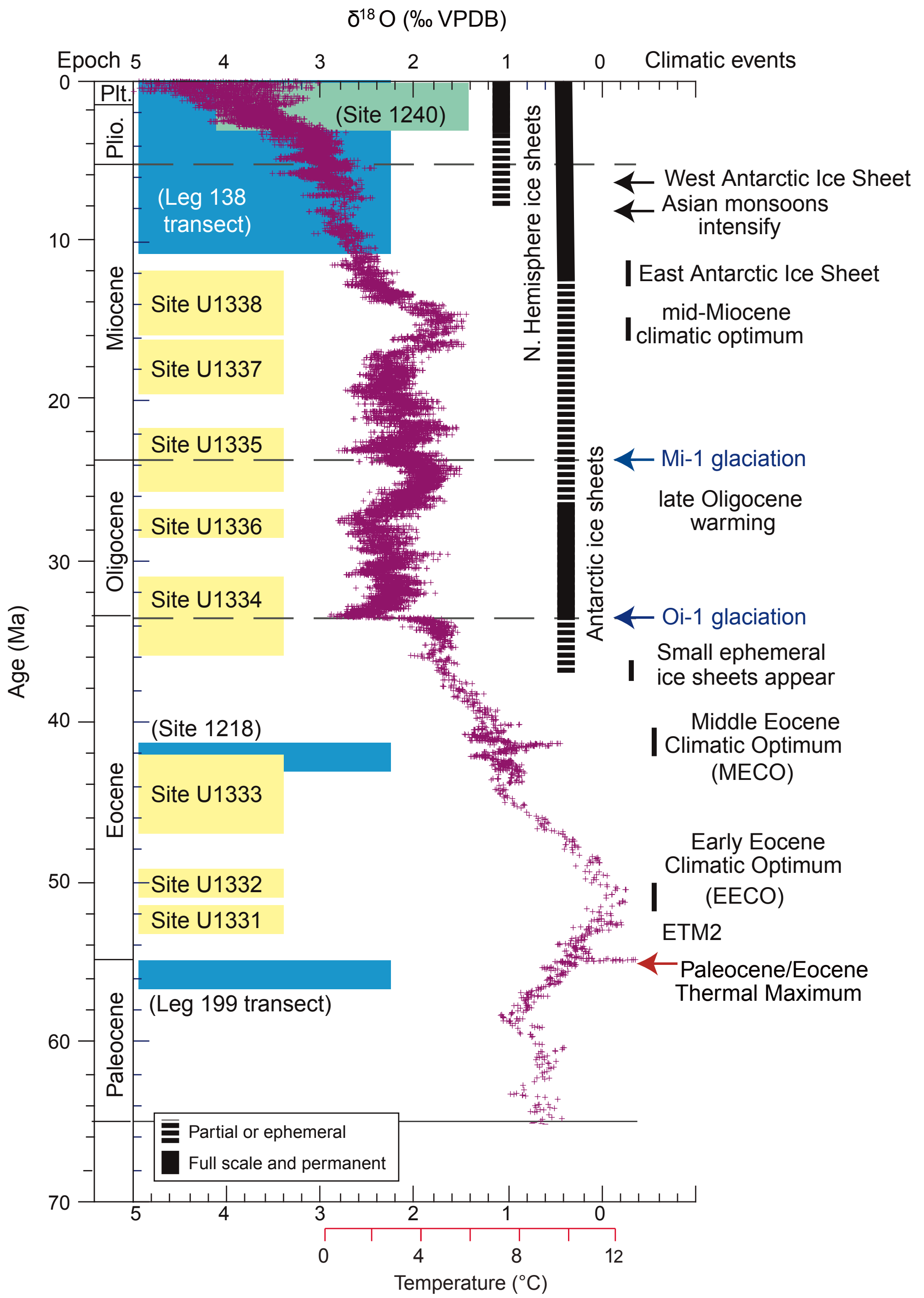

Figure 3. Evolution of oxygen stable isotopes ($\delta^{18}O$) through the Cenozoic and related major phases of climate change (modified from Zachos et al., 2001a, 2008). Yellow boxes = time slices of interest for the PEAT program, green and blue boxes = ODP legs and sites previously drilled in the equatorial Pacific region. These additional sites will be used with the PEAT sites to obtain a nearly continuous Cenozoic record of the equatorial Pacific region. VPDB = Vienna Peedee belemnite. Oi-1 = Oligocene isotopic Event 1, Mi-1 = Miocene isotopic Event 1 (Miller et al., 1991). ETM2 = Eocene thermal maximum 2.

For PEAT, we planned a flow line strategy to collect carbonate-bearing equatorial sediment sections through the Cenozoic (Fig. 2), making use of the Pacific plate motion to add an oblique latitudinal transect across all time slices, and also exploiting crustal subsidence to collect limited paleodepth transects for certain time slices. We drilled a series of sites in the paleoequatorial region spanning key intervals of Cenozoic climate evolution. These intervals include the extremely warm early Eocene, the cooling of the late Eocene through Oligocene, the relatively warm climates (or low ice volume) of the early Miocene, and sections deposited during development of major Southern and Northern Hemisphere ice sheets (Fig. 3). Each site was chosen close to the geographic paleoequator at critical age intervals on ocean crust slightly older than the intervals of particular interest.

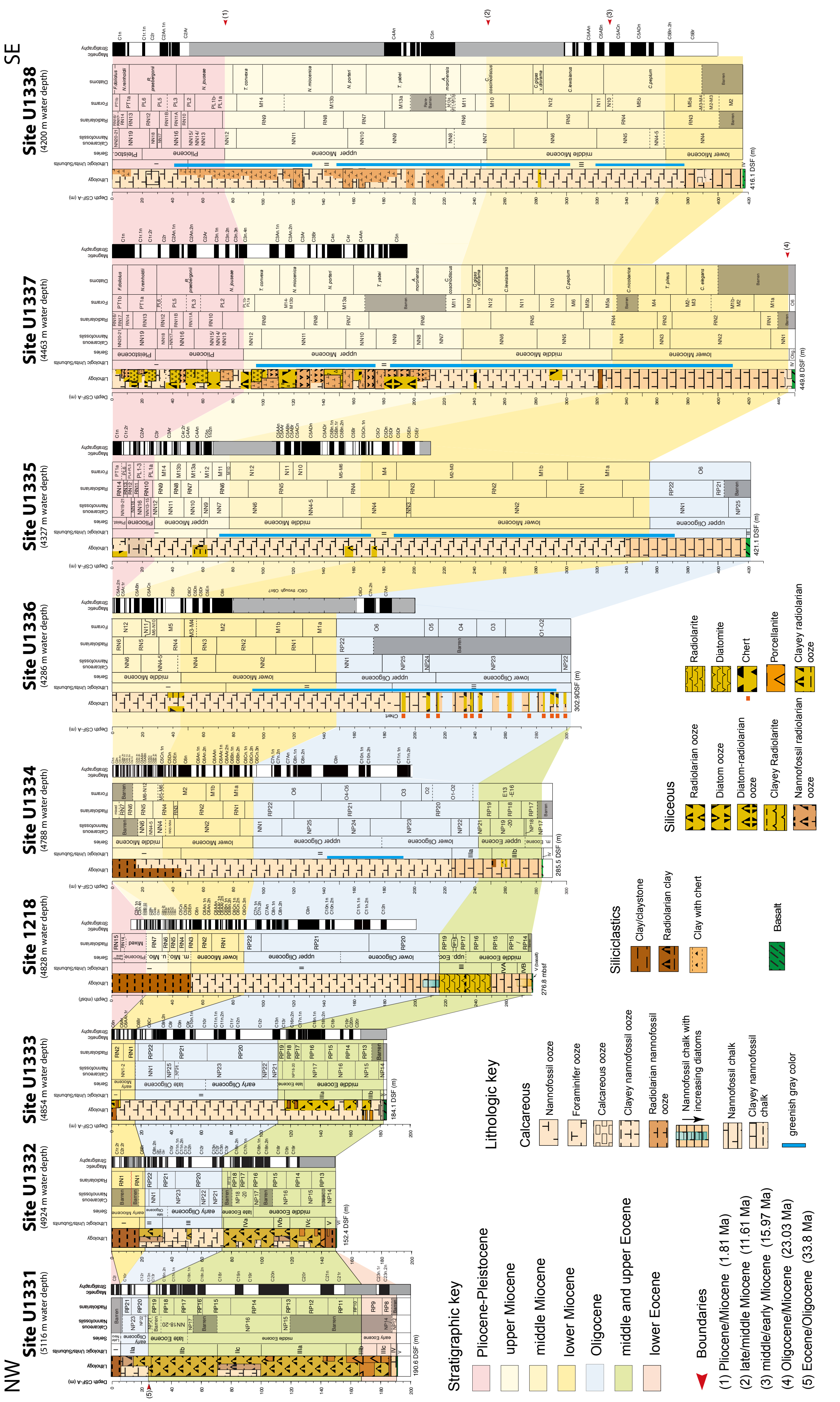

Figure 4. Stratigraphic summary plot for PEAT drill sites and ODP Site 1218. For each site the stratigraphic column and lithology are plotted against drilled depth, together with the magnetostratigraphy and biostratigraphic zonation schemes. The Eocene intervals are shaded in green, Oligocene in light blue, Miocene in dark and light shades of yellow, and Pliocene-Pleistocene in pink.

In this way we were able to track the paleoceanographic conditions at the paleoequator in the best preserved sediments obtainable. We can also make use of the high level of correlation between tropical sediment sections and seismic stratigraphy to develop a more complete model of equatorial productivity and sedimentation.

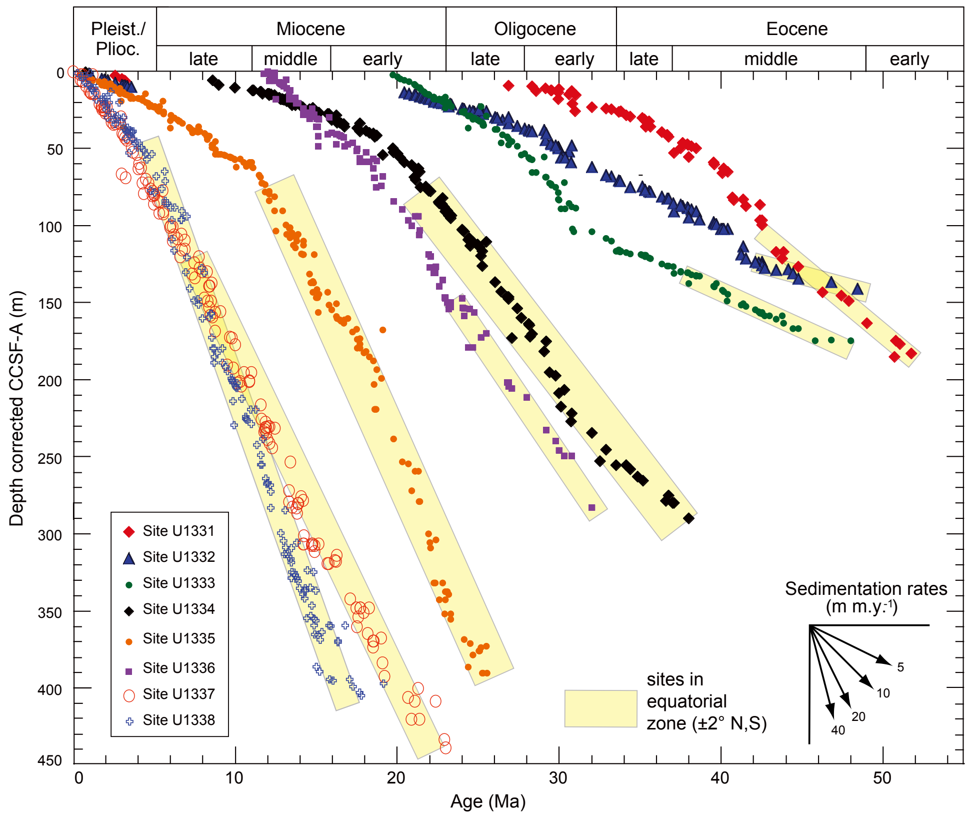

Figure 5. Summary of chronostratigraphic datum levels identified at PEAT sites plotted versus corrected composite depth (spliced depth compacted back to depth measured by the drill string). A steeper slope corresponds to a higher sedimentation rate. Yellow boxes mark approximate times when each drill site was within the equatorial zone (±2° N or S of the equator) based on estimated absolute motion of the Pacific tectonic plate.

Drilling Results

Detailed descriptions of PEAT drilling can be found in the Exp 320 and Exp 321 Preliminary Reports (see Related Web Links), and in the Exp 320/321 Initial Reports (in press). Eight sites (U1331 to U1338) were drilled; their basement ages span from 52 Ma to 18 Ma. PEAT shipboard science has determined that the sediments recovered fill gaps from previous drill-ing and can be used to create a high-resolution megasplice of equatorial Pacific sedimentation. Cross-calibration of magneto-, bio-, and ultimately orbital stratigraphy will significantly improve chronological estimates of sedimentation and ages of significant events. The study of fluxes of different sediment components will then add a new dimension of information about biogeochemical cycling.

The PEAT program recovered sediments similar in lithology to previous DSDP and ODP expeditions to the central equatorial Pacific region (Lyle et al., 2002). Figure 4 summarizes the lithostratigraphy of the northwest—southeast transect of sites drilled during Expedition 320/321 together with the sedimentary sequence from ODP Site 1218, which is also included in the PEAT flow line strategy. As expected due to the decreasing age of crust toward the southeast, the Eocene sequence (Fig. 4, green shading) thins from northwest to southeast, pinching out east of Site U1334, the last site drilled on Eocene crust. In contrast, the Miocene sequence (Fig. 4, yellow shading) thickens substantially from northwest to southeast. The Miocene section is thickest at Site U1337, which targeted crust of latest Oligocene age, and thus is the drill site that spent the most time within the Miocene equatorial zone. The Oligocene sequence (Fig. 4, blue shading) is thickest in the middle of the PEAT transect (U1334 and U1336) and thins in both directions, marking the Oligocene equatorial zone.

The study of paleoceanographic processes—and the variations and evolution over time of mass accumulation rates across the PEAT transect—depend on a detailed knowledge of sedimentation rates. The integrated bio- and magnetostratigraphies obtained for all expedition sites are the starting point to allow us to fully exploit and understand the complex interplay of productivity, dissolution, and spatial biogenic sedimentation patterns. The sedimentation rates vary from site to site over time depending on crustal subsidence, crustal age, and the length of time spent in the equatorial region (Fig. 5).

Our results reveal the change of linear sedimentation rate in both the latitudinal and age transect components of the PEAT program. The comparison between sites reveals that the highest sedimentation rates occur within the Oligocene and Miocene equatorial zones (Sites U1334 to U1338), with sedimentation patterns similar to the modern equatorial region (highest deposition at the equator). However, sedimentation rates within the Eocene equatorial zone were not significantly higher than those outside of the equatorial zone. This result will be confirmed with revised estimates post-cruise of Pacific plate motion vectors.

Time-dependent changes in sediment production and preservation strongly affected the Eocene sedimentary record. The linear sedimentation rates of the middle Eocene were high for the pelagic realm, frequently over 10 m m.y.$^{-1}$, with a maximum of 18 m m.y.$^{-1}$ at Site U1331. Rates for the middle Eocene at Sites U1332 and 1333 were similar (6–8 m m.y.$^{-1}$). The sedimentation rates during the late Eocene decreased to 3.5–6 m m.y.$^{-1}$ at Sites U1331 through U1333. Sediment-ation rates were highest (>20 m m.y.$^{-1}$) during the early to late Oligocene at Sites U1333 and 1334, and in the early and middle Miocene at Sites U1337 and U1338.

All sites have either a hiatus or reduced sedimentation rates for the youngest sediments because they have moved out of the Neogene equatorial zone and into regions with low modern deposition rates. The data from the PEAT sites,—when combined with available data from ODP Leg 138 for 0–10 Ma and ODP Leg 199 for intervals between 32 Ma and 42 Ma (Site 1218) and >52 Ma (Sites 1219 to 1221),—will produce a continuous history of sedimentation rates in the equatorial Pacific region for the past 56 m.y.

The combined results of ODP Leg 199 and the PEAT program provide the ability to study important intervals of climate change during the Cenozoic within the equatorial Pacific, and significant post-cruise research is aimed at these intervals. Important climate intervals include the early Eocene climatic optimum (EECO, Zachos et al., 2001a; Lyle et al., 2002; Sites U1331 and U1332), the middle Eocene climatic optimum (MECO; Bohaty and Zachos, 2003; Bohaty et al., 2009; Site U1333), the middle through late Eocene carbonate accumulation events (Lyle et al., 2005; Sites U1333 and U1334), the Eocene-Oligocene (EO) transition (Coxall et al., 2005; Site U1334), the late Oligocene warming (Pälike et al., 2006a; Site U1336), the Oligocene-Miocene (OM) transition (Zachos et al., 2001b; Pälike et al., 2006b; Sites U1335, U1336, and U1337), and the middle Miocene glaciation intensification event (Holbourn et al., 2005; Sites U1337 and U1338).

Initial Results and Future Directions

The highest shipboard priorities for a paleoceanographic drilling program are the development of a detailed sediment stratigraphy and the identification of a continuous sediment section that can be spliced together from multiple holes drilled at each site. In contrast, most of the scientific insight comes after drilling ceases and the scientific party has a chance to analyze samples collected from the cores along the spliced sedimentary sections. The sediment sampling was completed at the end of October 2009, and the analyses are just beginning. Nevertheless, broad-scale patterns can be discerned, and initial data have provided tantalizing indications of future results.

Because of the drilling design, the PEAT program was successful in collecting carbonate sediments of the late Eocene age and crossing the Eocene-Oligocene boundary. Carbonate sediments were also recovered for significant parts of the Eocene where it had been impossible from previous equatorial Pacific drilling to study the proxy climate information stored in carbonates. In addition, the Neogene PEAT sites are the first essentially complete Miocene sediment sections from the equatorial Pacific. These Miocene sediment sections will provide the first high-resolution studies of this poorly understood Cenozoic interval. Stable isotope studies on all the new sedimentary sequences will provide the backbone of information to understand the interrelationships between development of polar ice and equatorial circulation.

We also expect to recover important data about sea-surface temperature. Reconnaissance studies of alkenones (C. Beltran, unpublished) show a 4°C cooling of the equatorial Pacific since the middle Miocene. Most of the PEAT sediment splices are now being scanned using X-ray

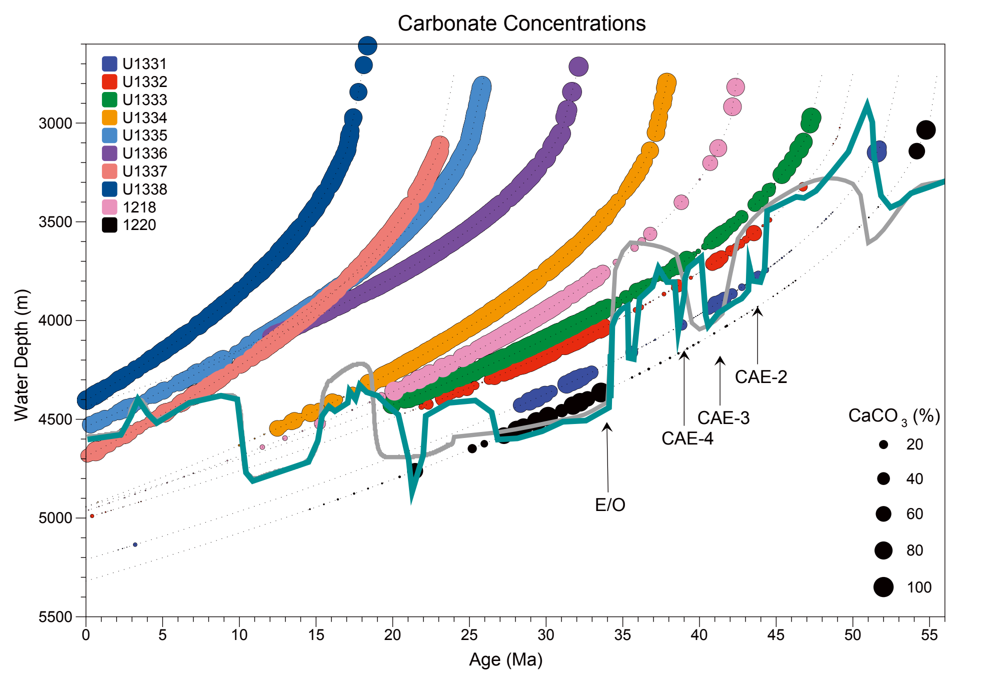

Figure 6. CaCO3% vs. depth and age from initial analysis of PEAT results. The carbonate compensation depth (CCD) through the Cenozoic is shown to be very dynamic during the Eocene, with many excursions of ~500 m. The Neogene has generally a deeper CCD and milder excursions.

Fluorescence (XRF) to collect high-resolution profiles of chemical data for much of the time interval. Furthermore, quantitative studies of microfossil assemblages will give new insights into the changes in the equatorial Pacific ecosystem, including the development of a diatom-based ecology in the late middle Miocene, with significant monospecific diatom intervals during the transition (Kemp and Baldauf, 1993). Finally, downhole logging will enable refinement of the equatorial seismic stratigraphy developed by Mayer et al. (1985) from Deep Sea Drilling Project Leg 85.

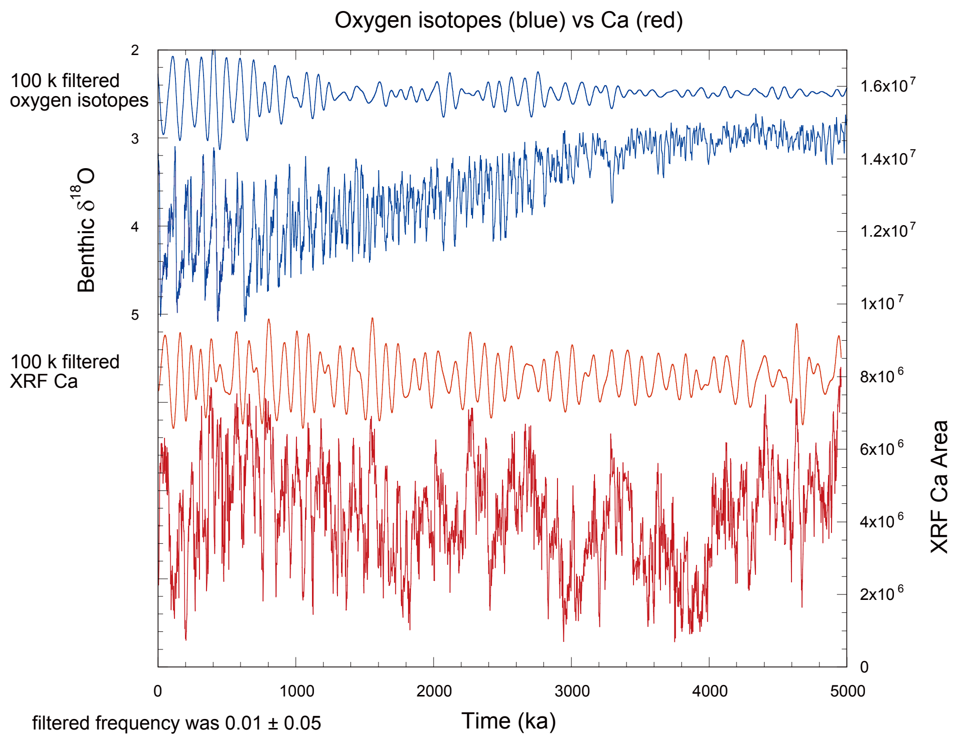

Figure 7. Oxygen isotope stack of Lisiecki and Raymo (2005) plotted against Ca peak area from XRF scanning (a measure of $CaCO_3$ content) at Site U1338. Also plotted are 100-kyr bandpass filter records (Gaussian filter with frequency of 0.01 kyr^{-1} ±0.005). Initial analysis suggests that the 100-kyr period in the XRF Ca area record is a dissolution cycle because it is not present in the shallower sediments recovered by ODP Leg 138. There is a strong 'eccentricity' cyclicity in the deep Pacific even when polar ice, represented by oxygen isotopes, was waxing and waning with a 41-kyr period prior to 1 Ma.

One of the key achievements of the shipboard scientific program was better constraint of Cenozoic stratigraphy, showing the potential to achieve detailed bio-, magneto-, and chemostratigraphies for the Cenozoic from the early Eocene to the present, within an astronomically tuned age model. Shipboard results indicate that we can achieve this objective based on the observation that even decimeter-scale features in the sedimentary record from the drilled sites can be correlated over large distances across the Pacific sea-floor (Pälike et al., 2005). The PEAT program will leave a lasting legacy through detailed correlation of all major fossil groups, a detailed magnetostratigraphy with over 800 dated reversals, and sedimentary cycles that can be correlated across large distances in the Pacific Ocean.

One of the primary objectives of the PEAT program is to detail the nature and changes of the CCD throughout the Cenozoic in the paleoequatorial Pacific (see text box on page 5), with potential links to organic matter deposition (Olivarez Lyle and Lyle, 2006). The choice of drilling locations, specifically targeting positions on the palaeoequator—to track carbonate preservation during crustal subsidence through time (Fig. 2)—followed the initial work on DSDP sites by van Andel et al. (1975). The first PEAT reconstruction of the Cenozoic CCD (Fig. 6) was augmented by additional results from ODP Leg 199 (Lyle et al., 2005; Rea and Lyle, 2005). One of the very significant contributions of Leg 199 drilling was the latitudinal mapping of CCD variations with time. During the Eocene, a generally shallow CCD appeared to be deeper outside a zone ±4° from the equator, opposite the pattern established during the Neogene (Lyle, 2003). The PEAT cores allow us to refine our knowledge of temporal and spatial variation in sediment accumulation rates resulting from plate movement, varying biologic productivity at the equatorial divergence, and carbonate preservation (Fig. 6). The shipboard determinations of $CaCO_3$ concentrations reveal the carbonate accumulation events of Lyle et al. (2005) as sharp carbonate concentration fluctuations at ~44 Ma, 41 Ma, 39 Ma, and 36 Ma across Sites U1331 through U1334 and ODP Site 1218, followed by a sharp transition into much higher carbonate accumulation rates from the Eocene into the Oligocene. PEAT shipboard results reveal a complex Eocene latitudinal pattern, where Sites U1331, U1332, and U1334 track the equatorial CCD that well matches the signal observed from ODP Site 1218. On the other hand, Site U1333, which is slightly to the north of the equatorial zone during the E-O transition, shows significantly more carbonate accumulation.

The early Eocene equatorial CCD was much shallower than previously thought. Site U1332, drilled on 50-Ma crust, recovered very little carbonate in the basal sediment section, in contrast to Site U1331 that is just ~two million years older. The estimated equatorial Pacific CCD at ~49 Ma is <3000 m paleodepth. Surprisingly, the late Oligocene (23–27 Ma) CCD was also found to be 300 m shallower than previously estimated. This shallower CCD, at a paleodepth of approximately 4.5 km, along with associated reduced carbonate fluxes to the sea-floor, may be linked to a late Oligocene warming before the O/M boundary. The O/M boundary interval was first fully recovered in the equatorial Pacific at ODP Site 1218 (Fig. 3; see also suppl. Fig. 3 in Pälike et al., 2006a). Neogene carbonate minima are well documented in the Neogene PEAT sites, including a CCD minimum between 17 Ma and 18 Ma, a 'carbonate crash' interval around 10 Ma, and a newly delineated CCD minimum at about 4 Ma that occurs concurrently with enhanced deposition of diatomaceous sediments. The design of our drilling locations in combination with existing data will allow us to generate a three-dimensional view of Cenozoic CCD evolution during post-cruise research and to explore the linkage between Cenozoic changes in atmospheric CO_2 and global warmth.

Post-cruise research will undoubtedly enhance our understanding of the strength and timing of the CCD events and how they relate to other globally important Earth systems. These studies are intended in part to develop the tie between these events and orbital insolation changes. Reaching a sample resolution high enough to detect orbital insolation variations is an important PEAT objective, necessary to improve the Cenozoic age model and to confirm that events across the equatorial Pacific are synchronous.

Initial XRF scanning results from the Neogene (Lyle et al., unpublished) using the new Texas A&M XRF scanner at the IODP Gulf Coast Repository demonstrate how important information will result from detailed studies of the PEAT sediment (Fig. 7). Shown is a comparison between the 0–5 Ma XRF Ca peak area in Site U1338 and the Lisiecki and Raymo (2005) LR04 benthic oxygen isotope stack. The Ca peak area is correlated to the CaCO3 content in the U1338 sediments. The age model used in this example for U1338 is the linear shipboard age model, which has not been further tuned.

The benthic isotope record clearly shows a progression from low amplitude 41-kyr obliquity cycles to higher amplitude 41-kyr cycles at 2.7 Ma, and finally to the dominance of 100-kyr eccentricity cycles by 1 Ma. The development of the 100-kyr power within the oxygen isotope record is most easily observed in the 100-kyr bandpass filtered isotope record. For the oxygen isotope record older than 1 Ma, the spectral power in the 100-kyr band is only about 0.2 times that of the 41-kyr band. The evolution of the benthic isotope record may be caused by the development of Northern Hemisphere ice sheets or at least increased sensitivity to

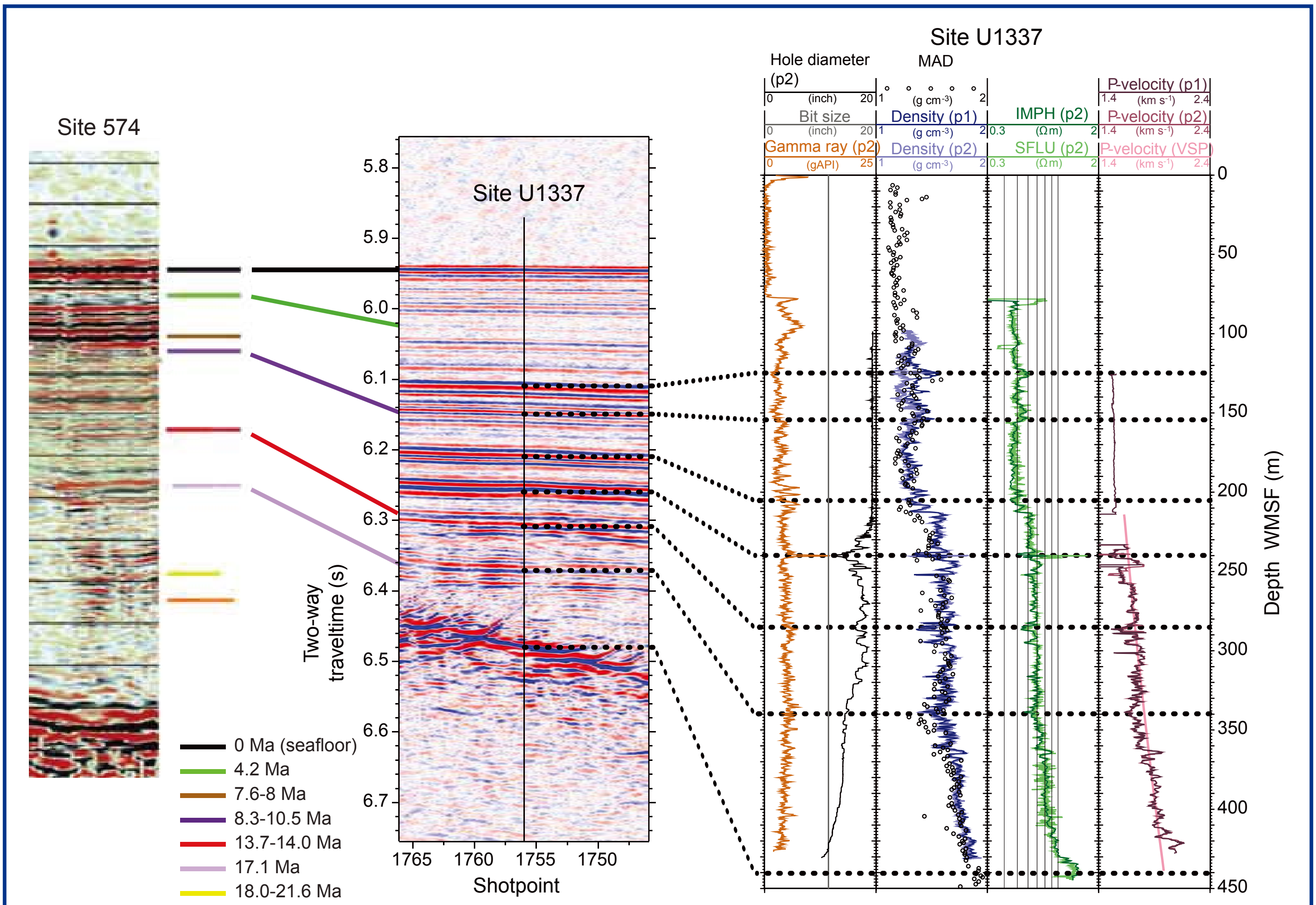

Figure 8. Correlation between the seismic reflection records from DSDP Leg 85 Site 574, IODP Expedition 321 Site U1337 (line 4 of the AMAT-03 site survey in the PEAT-7 area), and logging data from Hole U1337A. Correlations between the seismic profile at Site U1337 and the logs are based on velocities from VSP experiments and those measured by the velocity log, as well as the correlations to the age of sediments associated with the sediment physical property anomalies. The seismic horizons are associated with major fluctuations of carbonate; they appear to be chronostratigraphic, as originally suggested by Mayer et al. (1986).

high latitude insolation prior to the late Pleistocene (Lisiecki and Raymo, 2005).

In contrast, the U1338 Ca record retains spectral power in the 100-kyr band throughout the five-million-year record, suggesting that there is a linkage between carbonate burial and eccentricity (Pälike et al., 2006a). For the interval older than 1 Ma, the 100-kyr power in the Ca record is roughly six times greater than the 41-kyr power. It is interesting to note that records for 0–6 Ma from ODP Leg 138 eastern Pacific sites did not record high 100-kyr power (Hagelberg et al., 1995), but they do find high variability associated with obliquity (41 kyr) and precession (23 kyr and 19 kyr). The significant level of 100-kyr power in the older, deeper PEAT site suggests that dissolution (changes in CO_2 storage) may play a significant role in the development of the ~100-kyr $CaCO_3$ cycle in the central Pacific. Furthermore, it leads to the speculation that the abyssal carbon cycle played a role in 'looking in' the glacial cycles to a ~100-kyr rhythm.

Another major objective of PEAT drilling was to ground-truth the equatorial Pacific seismic stratigraphy so that seismic reflection records can be used to connect the sediment column described at each drill site to form a regional model. The PEAT expeditions have collected important new physical property data so that we can confirm the Mayer et al. (1985) seismic stratigraphy and also tie the eastern Pacific seismic stratigraphy with that of the central Pacific.

The equatorial Pacific is a classic 'binary' sediment system, with variable amounts of biogenic calcium carbonate and biosiliceous sediment components but very little clay. It is also well known that carbonate contents of equatorial Pacific sediments can be estimated from the bulk density, because carbonates have lower porosity and higher grain density than biosiliceous sediments (Mayer, 1991). Consequently, physical properties records contain meter-scale cyclicity that will ultimately be useful for orbital-tuning time scales, which is one of the PEAT objectives. Mayer et al. (1985) developed a seismic stratigraphy for the central Pacific at Site 574 on DSDP Leg 85. They noted that major seismic horizons were caused by density variations associated with low carbonate intervals. They proposed that the seismic horizons were isochrons because they were caused by paleoceanographic changes in deposition and/or dissolution of calcium carbonate.

Mayer et al. (1985) did not have logs to measure *in situ* velocities in support of their interpretation. One of the important PEAT experiments therefore was to use a combination of downhole measurements (vertical seismic profile (VSP) and standard logs) with physical properties measurements on core. We were able to run the VSP log at Site U1337 (Fig. 8) and Site U1338. Figure 8 is an initial comparison between the Site 574 seismic stratigraphy of Mayer et al. (1985) and the shipboard results for Site U1337. The events correlate in age, as would be predicted by Mayer et al. (1985). Site 574 is at essentially the same latitude as Site U1337 but is located more than 1000 km to the west. The extent of the correlatable seismic horizons across the Pacific helps to define the magnitude of the paleoceanographic events that caused them. Post-cruise studies will focus upon better defining the seismic strati-graphy at both Sites U1337 and U1338, allowing new tie points for seismic stratigraphic study of the equatorial Pacific sediment bulge (Mitchell et al., 2003).

Outlook for the Future

The initial results from PEAT drilling illustrate the fundamental thrusts of the post-cruise science and provide a taste of new scientific insights to be reported in the next few years. We expect these insights to include a fundamental improvement of the Cenozoic time scale, an exploration of the unstable Eocene CCD and its relation to atmospheric CO_2, a much better understanding of the interactions between the carbon cycle and climate, and a better understanding of the history of major pelagic nutrient cycles and productivity. All of these studies will give important insights on how different Earth systems have interacted in the past and may respond in the near future.

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IODP Expedition 321T: Cementing Operations at Holes U1301A and U1301B, Eastern Flank of the Juan de Fuca Ridge

by Andrew T. Fisher, and IODP Expedition 321T Scientific Party

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Introduction

IODP Expedition 301 (Fisher et al., 2005a) was part of a series of expeditions and experiments to quantify hydrogeologic, lithologic, biogeochemical, and microbiological properties, processes, and linkages on the eastern flank of the Juan de Fuca Ridge, North Pacific (Fig. 1). Operations during Expedition 301 included replacement of one existing subseafloor borehole observatory ("CORK", Hole 1026B), drilling two basement holes and installing two new long-term observatories (Holes U1301A and U1301B), coring the upper ~300 m of basement and shallow sediments above basement, and collection of *in situ* hydrogeologic and geophysical data from basement. Subsequent expeditions using a remotely operated vehicle (ROV) and submersible have serviced borehole observatories, collected pressure and temperature data and fluid and microbiological samples, and replaced components as needed to maintain these systems for future use. Another drilling expedition is planned for 2010 (see backcover for schedule) to emplace three more borehole observatories and initiate cross-hole tests, and additional ROV and submersible ex-peditions will conduct long-term experiments and recover subseafloor data and samples.

Borehole observatories installed during IODP Expedition 301 were designed (i) to seal open holes so that thermal, pressure, and chemical conditions could equilibrate following the dissipation of the drilling disturbance; (ii) to facilitate collection of fluid and microbiological samples and temperature and pressure data using autonomous samplers and data logging systems; and (iii) to serve as long-term monitoring points for large-scale crustal testing (Fisher et al., 2005b). Unfortunately, the CORKs installed in Holes U1301A and U1301B were not sealed as intended (Fisher et al., 2005a). Initially, both holes were drawing cold bottom seawater into basement, but as described below, conditions in these holes are dynamic, and flow conditions have changed over time. The primary objective of Expedition 321T was to seal these observatories by pumping cement into the reentry cones surrounding the CORK wellheads, allowing the remaining components of the full experimental program to be completed during subsequent drilling and submersible expeditions.

Background

Ocean Drilling Program (ODP) Leg 168 completed a drilling transect of eight sites across 0.9–3.6 Ma seafloor east of the Juan de Fuca Ridge. It resulted in collection of sediment, rock, and fluid samples; determination of thermal, geochemical, and hydrogeologic conditions in basement; and installation of a series of CORK observatories in the upper crust (Davis et al., 1997). Two of the Leg 168 observatories were placed in 3.5–3.6 Ma seafloor near the eastern end of the drilling transect, in Holes 1026B and 1027C (Fig. 1). IODP Expedition 301 returned to this area and drilled deeper into basement, sampled additional sediment, basalt, and microbiological materials, replaced the borehole observatory in Hole 1026B, and established two multilevel observatories at Site U1301 for use in long-term, three-dimensional hydrogeologic experiments.

Hole 1026B was drilled to 295 meters below seafloor (mbsf), cased across the sediment/basement interface, and extended to 48 meters sub-basement (msb) during ODP Leg 168 (Davis et al., 1997). The original CORK installed in Hole 1026B included a data logger, pressure sensors, thermistors at multiple depths, and a fluid sampler, all of which (except the fluid sampler) were recovered in 1999. The Hole 1026B CORK was incompletely sealed after being installed in 1996, and because basement fluids are overpressured in this location with respect to ambient hydrostatic conditions (Davis, et al., 1997), this hole discharged fluid for years until it was replaced during IODP Expedition 301. As of the start of Expedition 301, warm (~64°C) altered basement fluid vented freely through the top of the wellhead. The original ODP Leg 168 CORK installed in Hole 1026B was replaced successfully during IODP Expedition 301.

IODP Site U1301 was positioned 1 km south-southwest of ODP Site 1026, where sediment thickness is 260–265 m above a buried basement high (Fig. 1). Hole U1301A was drilled without coring to 370 mbsf (107 msb). The casing was extended into the upper 15 m of basement, but poor hole conditions prevented installation of longer casing, coring, or deeper drilling. A depth check prior to CORK deployment in Hole U1301A revealed that much of the lower part of the hole had filled in with rocks from the rubbly formation around the hole.

Hole U1301B was position-ed 36 m away. It penetrated to a total depth of 583 mbsf (318 msb). Uppermost basement was drilled without coring, and casing was installed to 85 msb. Basement was cored from 86 msb to 318 msb. The upper 100 meters of the cored interval in Hole U1301B were irregular in diameter, often much larger than the maximum inflation diameter of packers to be used for hydrogeologic testing and CORK observatries. However, the lower 100 meters of the hole were stable and to gauge, allowing collection of high-quality wireline logs and providing several horizons suitable for setting drill string and CORK casing packers.

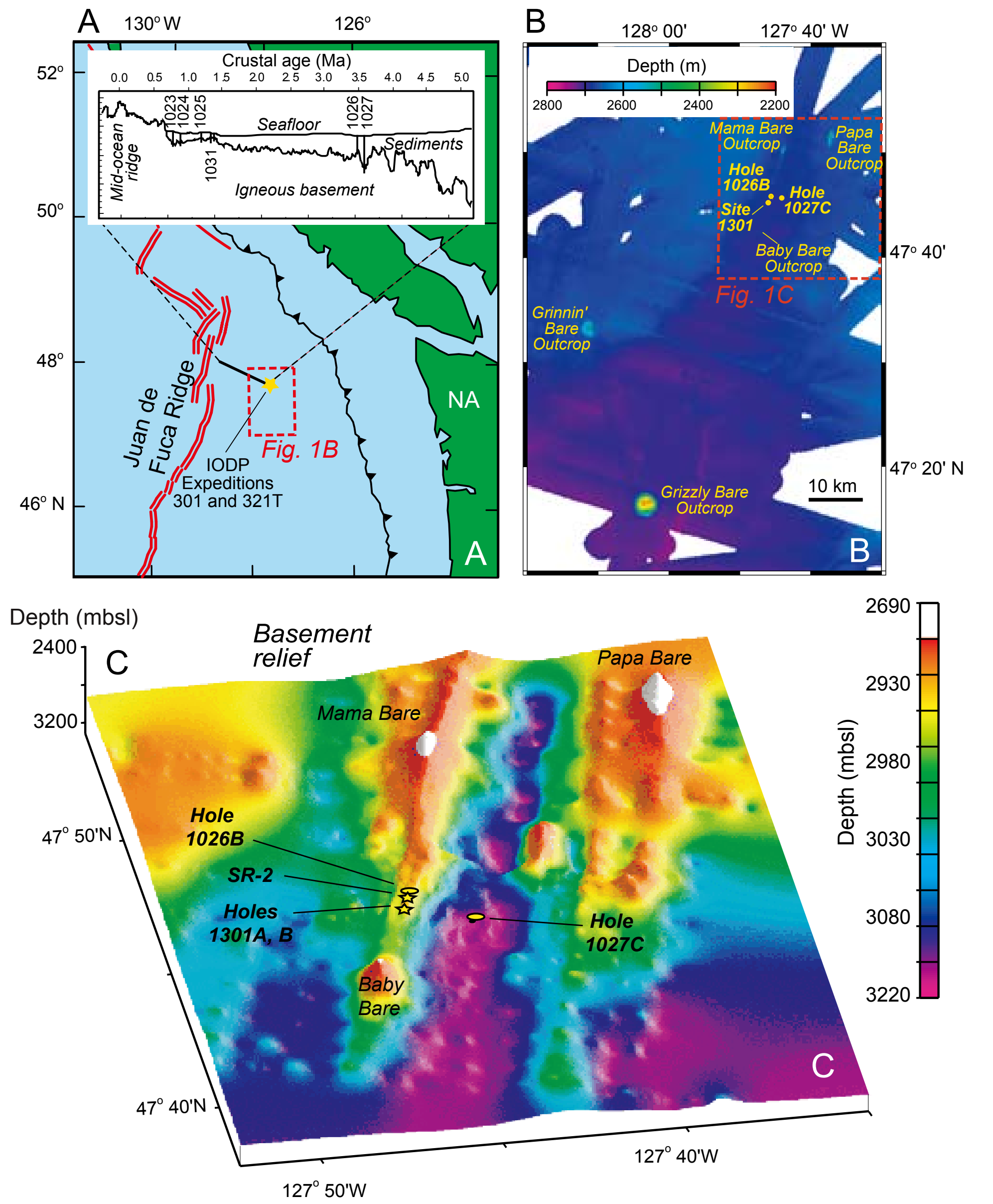

Figure 1. Maps showing the IODP Expedition 301 and 321T field area. [A] Index map showing locations of ODP Leg 168 drilling transect (thick black line), IODP Expedition 301 and 321T work area (gold star), the Juan de Fuca Ridge, and nearby continental areas. Inset profile shows locations of ODP Leg 168 sites. [B] Regional bathymetric map showing locations of ODP Holes 1026B and 1027C and IODP Site U1301. [C] Map of basement relief created from bathymetric and seismic data, showing locations of ODP and IODP drill sites. Areas marked in white are present-day basement outcrops. Figure modified from Zühlsdorff et al., 2005.

Both of the Site U1301 boreholes contained four nested casing strings: a 0.50-m casing (20-inch diameter) in the uppermost sediments, a 0.41-m casing (16-inch diameter) extending just across the sediment/basement interface, a 0.27-m casing (10.75-inch diameter) extending into basement, and a 0.11-m inner CORK casing (4.5-inch diameter) that houses instrument strings and plugs (Fig. 2). The two largest casing strings were sealed by collapse of unconsolidated sediments, and the 0.41-m string was also cemented across the sediment/basement interface. The annulus between 0.41-m and 0.27-m casing strings at Site U1301 was supposed to contain a rubber, mechanical casing seal near the seafloor, but this component was not available for use during Expedition 301 as planned. An attempt was made to seal the 0.27-m casing strings at depth with cement, but rubbly basement prevented the cement from sealing between casing and the borehole wall. Operations were additionally complicated in Hole U1301B by the separation of the unwelded 0.27-m casing string into two sections, which left a gap just above the sediment/basement interface (Fig. 2b). The CORK installed in Hole U1301A included a casing packer (as part of the 0.11-m inner casing) that was set inside the 0.27-m casing. In contrast, the CORK installed in Hole U1301B included two casing packers set in an open hole intended to hydraulically isolate sections of the upper crust (Fig. 2b).

Expedition 301 CORKs and the preexisting CORK in Hole 1027C were visited with an ROV soon after drilling in September 2004, and again by submersible in September 2005. Data recovered during these dives showed that the Hole 1026B observatory was sealed and operating as intended, although the pressure in Hole 1026B was recovering slowly from the thermal perturbation associated with eight years of upflow of warm formation fluid. The CORKs in Holes U1301A and U1301B were incompletely sealed, allowing cold ocean-bottom water to flow into the formation following CORK installation. The flow of this water into the crust at Site U1301 caused a measurable pressure perturbation at Site 1027, 2.4 km away, comprising an unintended (but scientifically useful) cross-hole test (Fisher et al., 2008).

Attempts to seal Hole U1301B using a cement delivery system with the submersible *Alvin* in summers 2006 and 2007 were unsuccessful, as the submersible could not deliver a sufficient quantity of cement to the cone. Shimmering fluid was observed discharging from Hole U1301A during and after summer 2007 dive operations. No such evidence for upflow from the borehole was observed during earlier visits, suggesting that Hole U1301A had "turned around" sometime between 2006 and 2007 servicing operations. In fact, downhole temperature loggers recovered from Hole U1301A in summer 2008 provide a detailed record of this flow reversal. Remarkably, Hole U1301B continued to draw fluid rapidly into basement as of summer 2008, even though it is located just 36 m from Hole U1301A, which was vigorously discharging warm formation fluid to the ocean. Additional research will be needed to understand the pressure and thermal interactions between Holes U1301A and U1301B as well as the implications for local and regional crustal hydrogeology.

The CORK landing platform installed at Hole U1301A included a solid surface that was perforated by eight 25-cm-diameter holes. Screens were welded below these holes prior to deployment so that instrumentation being deployed or manipulated by a submersible or ROV would not fall through the holes. In contrast, the landing platform at Hole U1301B has a series of radial support arms covered by the same screen material as was welded to the bottom of the platform at Hole U1301A. By the time the landing platform was deployed at Hole U1301B during Expedition 301, shipboard personnel realized that later cementing would be necessary, and a slot was cut through the platform screen to facilitate this operation.

Operations and Results

A special formulation of cement, including "Cello-Flake" lost circulation material (LCM) was loaded onto the *JOIDES Resolution* during a brief port call prior to Expedition 321T. The use of cement with LCM is common in industry drilling and borehole installations, particularly in fractured rock, but this technology had not been used previously in scientific ocean drilling. In addition, a special bottom hole assembly

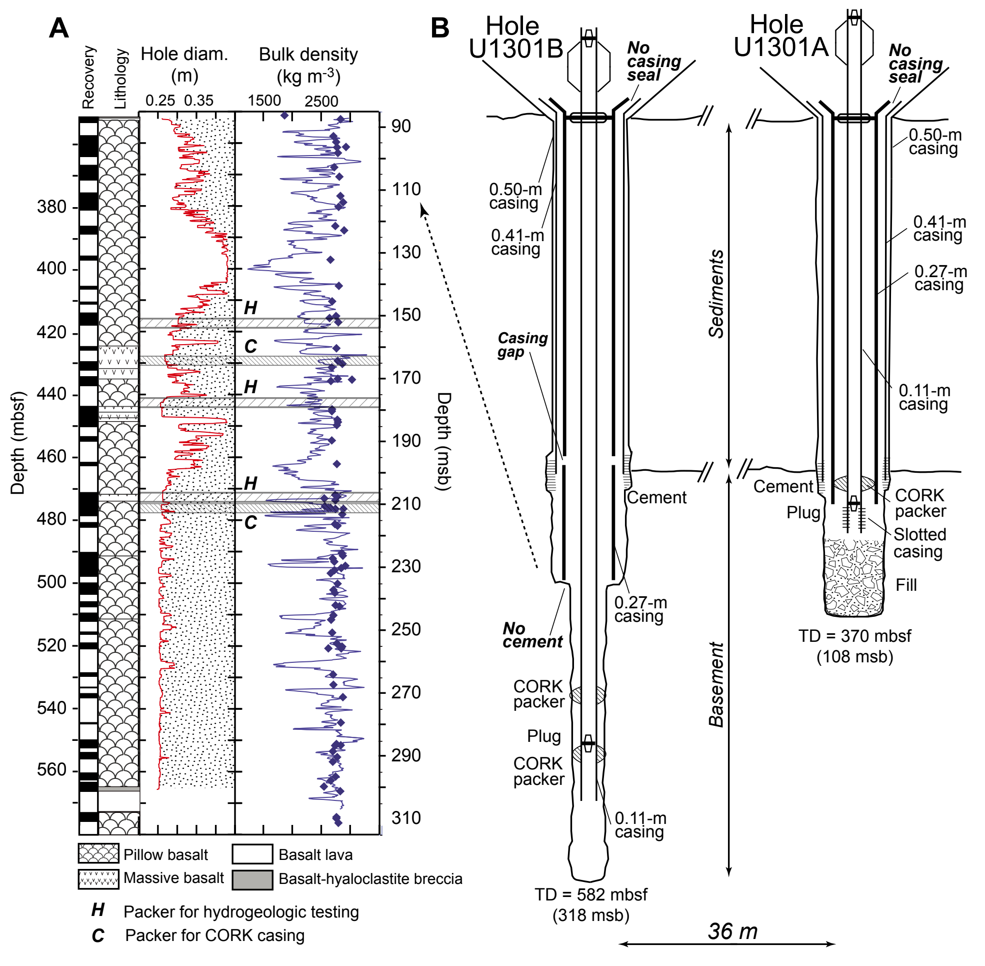

Figure 2. Summary of basement and borehole observatory characteristics in Holes U1301B and U1301A (modified from Fisher et al., 2008). [A] Basement recovery, primary lithology, borehole size, and bulk density from Hole U1301B (Fisher et al., 2005a). Basement cores were collected from ~355 mbsf to 575 mbsf (~100–320 msb), with recovery indicated by black intervals next to depth column. Bulk density log (blue line) and analyses of pieces of rock (diamonds) show evidence for considerable porosity in uppermost basement and a layered basement structure, especially below 470 mbsf (220 msb), with alternating more and less dense intervals. Horizontal bands indicate depths where CORK casing packers and the drill string packer used for hydrogeologic testing were set against the borehole wall. [B] Casing and CORK configurations in Holes U1301B and U1301A. Observatories in both holes lack a critical seal between 0.27-m and 0.41-m casing, which are needed to prevent the flow of cold bottom water into shallow basement or the flow of warm formation fluid out into the ocean. TD = total depth.

(BHA) was designed for Expedition 321T cementing operations, including a cementing "stinger" with a beveled edge that could be used to push through one of eight 25-cm-diameter holes in the landing platform in Hole U1301A.

Cementing operations occurred first at Hole U1301B, where reentry was easier because of the preexisting hole in the landing platform in the cone. Once pipe was run, reentry required 2.25 hrs, after which 60 barrels (bbls) of cement blended with LCM was pumped into the reentry cone. Seafloor operations were observed with the shipboard television camera system, and the cone was visibly filled with cement. The ship was offset to Hole U1301A, where the cement stinger was maneuvered to push through a screened hole in the CORK landing platform. This second reentry was accomplished in 2.75 hrs, after which 114 bbls of cement blended with LCM was pumped into the reentry cone. The ship was offset back to Hole U1301B, the hole was reentered again, and another 70 bbls of cement and LCM was pumped into the cone. Both reentry cones were inspected and found to be filled with cement surrounding the CORK observatory wellheads. Additional cement was observed to have poured over the edges of the cones and into the depressions in the seafloor around the cones. Cementing operations during 321T were completed more quickly, and with greater ease, than anticipated because of a combination of careful planning and preparation, the skill of the shipboard personnel in managing delicate operations, and fortuitous weather and sea conditions.

A scientific group returned to Holes U1301A and U1301B by submersible three weeks after Expedition 321T, downloaded pressure data, and evaluated the success of cementing efforts. As of summer 2009, both holes U1301A and U1301B had "turned around" and returned to overpressured conditions. Hole 1301A continued to leak fluid, as some of the cement pumped into the cone during Expedition 321T drained down into the annular gap between 0.41-m and 0.27-m casings. Additional cementing will be attempted during summer 2010 drilling operations, with a more aggressive use of LCM, to seal hole U1301A more completely. In contrast, Hole U1301B appears to be sealed between 0.41-m and 0.27-m casing, but the fluid overpressure in basement is greater than anticipated, and the top CORK plug was lifted by this pressure. Dive weights were placed on top of the plug during summer 2009 submersible operations, and additional pressure data will be collected from this system during summer 2010 servicing, which will allow a more complete evaluation of the state of this borehole observatory system.

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and IODP Expedition 321T Scientific Party

Drilling of Early Cretaceous Oceanic Anoxic Event 1a in Southern France

by Sascha Flögel and Wolfgang Kuhnt

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Introduction

The massive concentration of black, laminated, organic carbon-rich shales at certain time periods during the Cretaceous period (~140–65 Ma) led to the concept of Oceanic Anoxic Events (OAEs). These events are characterized by unusually enhanced preservation of organic matter across environments ranging from the deep oceans to shelf seas. Enhanced productivity of siliceous and organic-walled primary producers and/or strongly dysaerobic or anoxic conditions in all major oceans were both suggested as likely causes (Meyer and Kump, 2008). Fundamental chemical and biological changes in the world ocean must have been associated with these events.

While the geographic extent of most black shale events in the Cretaceous is still under debate, the two main OAEs in the early Aptian (Selli Event: OAE1a, ~119 Ma) and at the Cenomanian-Turonian boundary (Cenomanian/Turonian Boundary Event: OAE2, ~94 Ma) have proven to be of global distribution (Grötsch et al., 1998). Estimates of organic matter accumulation rates and recent findings of biomarkers for cyanobacteria, a proxy for photic zone anoxia in organic-carbon rich sediments of both OAEs, indicate high levels of productivity as observed in extreme upwelling environments today (Meyer and Kump, 2008). Carbon-isotope studies demonstrate that both the Aptian and the Cenomanian-Turonian black shales are associated with a positive carbon-isotope excursion in marine pelagic and shallow-water carbonate, marine organic matter, and terrestrial higher-plant material. These positive carbon-isotope excursions thus offer a means of correlation between sediments deposited in the oceans and on the continents. The Aptian event is also associated with an initial negative carbon-isotope excursion, recently interpreted as due to dissociation of methane hydrates. It has been suggested that both phenomena, OAEs and methane-release events, were results of increased global temperatures caused by high CO_2-levels in the atmosphere (Wagner et al., 2007). Massive sequestration of organic carbon during an OAE, however, would draw down CO_2 and produce global cooling with respect to pre-OAE levels (Forster et al., 2007).

After decades of research, timing and causes of onset and spread of Cretaceous OAEs still remain a topic of vigorous debate. Deciphering the driving mechanisms and time scales for the onset and spread of OAE1a is the main objective of this study. Due to the lack of complete, unweathered sections of the early Aptian, a well-studied type locality of early Aptian deposition in southern France was selected for coring.

La Bédoule section and coring

The drilling campaign took place during May 2009 at Roquefort-La Bédoule about 20 km southeast of Marseille. The drill sites are located in abandoned quarries in close proximity to outcrops with an existing stratigraphic framework (Figs. 1, 2). The target interval was successfully encountered below the weathering zone.

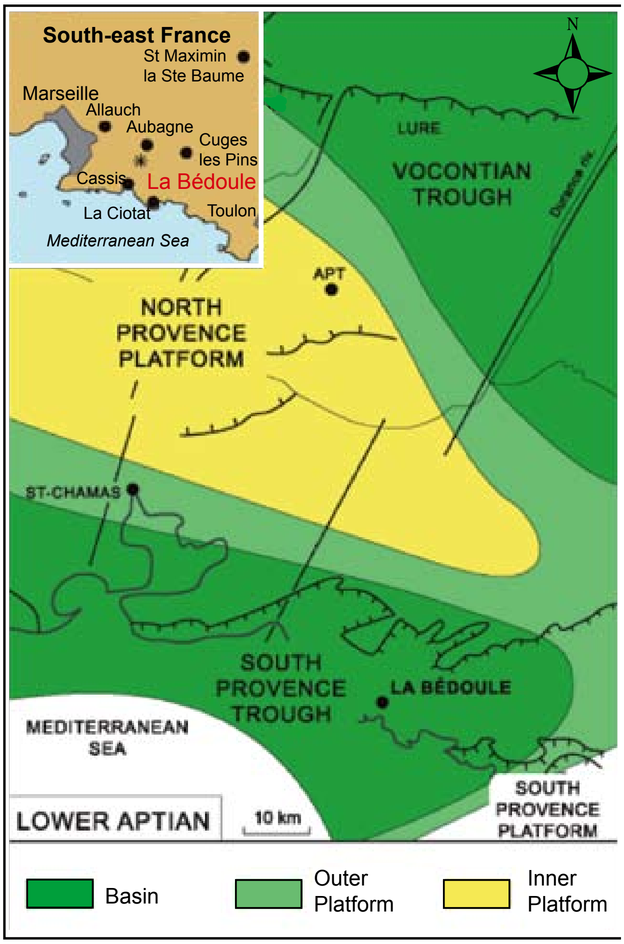

Figure 1. Paleogeographical scheme of the South Provence intrashelf basin during the Lower Aptian (from Renard et al., 2005) with location map of the La Bédoule-Cassis area in southern France (upper left corner).

Figure 2. Drilling operations at section LB1 with a trailer-mounted rig.

The regional and palaeogeographic setting of the stratotype is that of an intrashelf basin—the South Provence Trough—that formed within the Urgonian Carbonate Platform during late Barremian times (Masse et al., 1993). It was isolated from the Vocontian Basin to the north by the North Provence Platform (Monts de Vaucluse – Mont Ventoux) and bounded to the southeast by the South Provence Platform (Mont Faron). Although quite restricted in extent initially, this trough extended westward during Lower Aptian times to join the North Pyrenean Basin of the

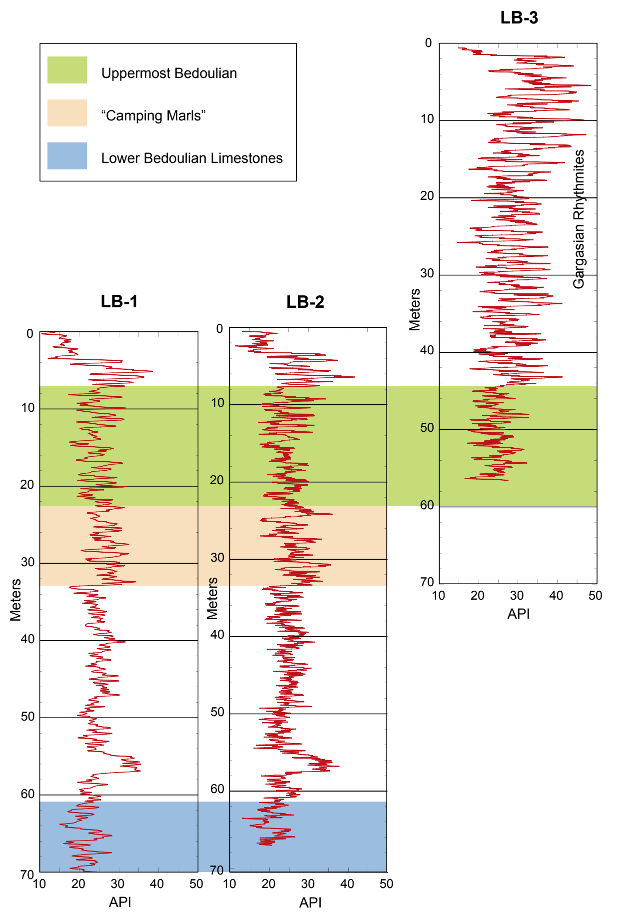

Figure 3. Geological sections and gamma-ray logs of cores drilled in the Aptian of La Bédoule.

'Deshayesites Marls' (Masse et al., 1993). As described by Moullade et al. (1998a, 1998b) and Masse (1998), the section at La Bédoule presents three lithological members:

- Upper Barremian-lower Bedoulian limestone member overlying the Urgonian Platform deposits
- Upper Bedoulian alternating marls and limestones member
- Top Bedoulian - lower Gargasian marly member

The discrimination of these members is of practical value in the field but does not accurately reflect the $CaCO_3$ content which always remains high (80–95%; Masse, 1998). The position of the main OAE1a carbon isotope excursion within the "Camping Marls" in the Upper Bedoulian alternating marls and limestones member is correlated bed by bed to a nearby outcrop section at the former camping ground of La Bédoule (Fig. 3). Three cores at two different sites were drilled with a total recovery of more than 180 meters and a core diameter of 11 cm. Of the three holes, two are covering lower Bedoulian limestones through uppermost Bedoulian sediments (LB1 = 70 m and LB2 = 67 m), while LB3 (56 m) recovered uppermost Bedoulian through middle Gargasian strata. The cores were retrieved continuously with 100% recovery and minimal disturbance at core breaks, which can be bridged by the parallel core in all cases. Cores were cut into working and archive halves and are stored under cool conditions in the core repository at IFM-GEOMAR, Germany.

Objectives

The drilling campaign was initiated to recover high quality sediment cores in order to determine the timing, succession of events, and feedback mechanism at the onset of OAE1a. Goals include times series analysis of continuously measured proxy data (gamma rays, visible light spectrometry, and XRF scanning) to develop orbital chronologies and to determine leads/lags between different proxy data. Additionally, it is planned to develop ultra-high resolution isotopic (δ^{13}Ccarb and δ^{13}Corg) records of the periods immediately before and during the initial carbon isotope shifts in the early Aptian. These will include proxy records for marine organic carbon accumulation (TOC Rock-Eval records), deep water oxygenation (benthic foraminiferal dissolved oxygen index, redox-sensitive elements such as Mn/Fe, U/Mo, Re/Mo, and Te/Se, and isotope systems such as $\delta^{98/95}$Mo), and SST (δ^{18}O, TEX86, and Ca-isotopes) at intermediate resolution and/or at critical points of the high-resolution data series. A further aim will be determining the amplitude and phasing of pCO_2 changes during the OAE as a crucial boundary condition for climate models by using boron isotopes (Pearson and Palmer, 2000).

Initial foraminiferal biostratigraphy indicated that the upper portion of LB2 top is still uppermost Bedoulian (Furcata zone) and that the top of LB3 can be attributed to the very basal *Globigerinelloides barri* zone (middle Gargasian). High-resolution wireline gamma-radiation of the cores was registered to serve for detailed cross-correlation of wells (Fig. 3).

High-resolution analyses of the core are currently underway, including foraminiferal and nannoplankton biostratigraphy (University of Marseille and University of Lyon), and visible light spectrophotometry, XRF scanning, and stable isotope geochemistry (University of Kiel). The advanced analytical phase of this multi-disciplinary project is scheduled for the next three years.

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Photo Credit

Fig. 2: S. Flögel

The Great Oxidation Event Recorded in Paleoproterozoic Rocks from Fennoscandia

by Victor A. Melezhik, Aivo Lepland, Alexander E. Romashkin, Dmitry V. Rychanchik, Melanie Mesli, Tor Erik Finne, Ronald Conze and the FAR-DEEP Scientists

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With support of the International Continental Scientific Drilling Program (ICDP) and other funding organizations, the Fennoscandia Arctic Russia – Drilling Early Earth Project (FAR-DEEP) operations have been successfully completed during 2007. A total of 3650 meters of core have been recovered from fifteen holes drilled through sedimentary and volcanic formations in Fennoscandia (Fig. 1), recording several global environmental changes spanning the time interval 2500–2000 Ma, including the Great Oxidation Event (GOE) (Holland, 2002). The core was meanwhile curated and archived in Trondheim, Norway, and it has been sampled by an international team of scientists.

Introduction

The emergence of an aerobic Earth System and a series of interrelated global events (Archean-Paleoproterozoic Transition, APT) during the Late Archean and Early Paleoproterozoic (2500–2000 Ma) led to the irreversible alteration of Earth's surface (Fig. 2). This environmental change poses a fundamental challenge in the geosciences (Melezhik et al., 2005a). The FAR-DEEP Expedition specifically targeted geological formations 2500–2000 Ma old in three different areas (Fig. 1) that recorded most of the events associated with the GOE. The project has three major goals:

- Establish a well-characterized, well-dated, and well-curated succession of rocks for the period of 2500–2000 Ma
- Document the changes in the biosphere and the geosphere associated with the rise in atmospheric oxygen
- Develop a model to explain the genesis and timing of the establishment of the aerobic Earth System.

The samples obtained by the FAR-DEEP provide a representative geological record of the most important global events occurring through the APT (Fig. 2).

Drilling Operations

The drilling operations were carried out from May to October 2007 on the Russian part of the Fennoscandian Shield. The fifteen holes drilled range in depth from 92m to 503 m, totaling 3650 m of recovered core. To minimize the risk of core contamination for forthcoming biomarker studies, the drilling was performed with clear water and with non-oil-based lubricants. In most cases, the core recovery was close to 100%. Most of the cores were successfully re-oriented, and they are suitable for paleomagnetic studies. The large distances and remoteness of the drilling sites with limited infrastructure required a considerable logistical effort. In addition the coring offered a unique opportunity for students from the FAR-DEEP partner institutions to examine field sites and participate in the recovery of the best available

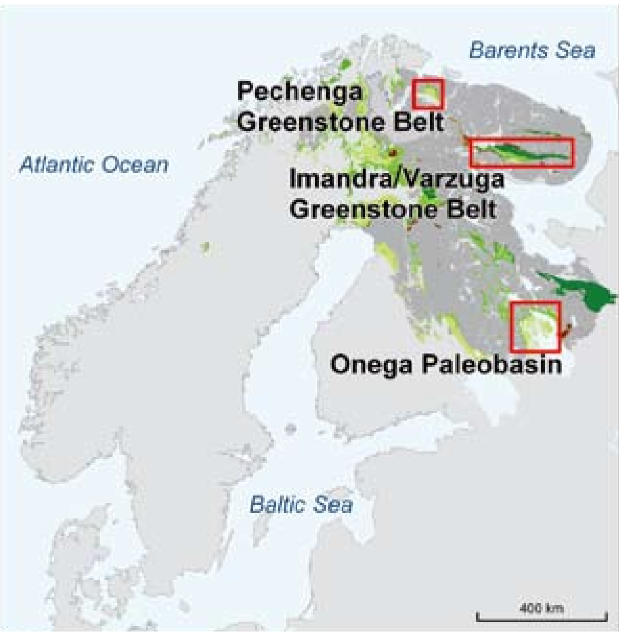

Figure 1. Geographic locations of the FAR-DEEP drilling operations.

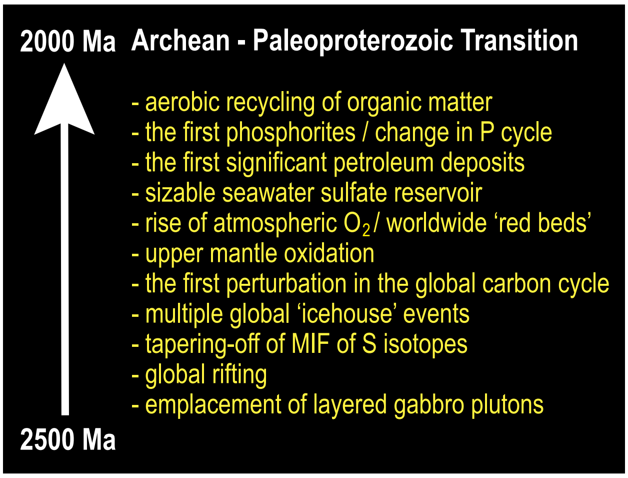

Figure 2. Global environmental events associated with the GOE, and targeted by FAR-DEEP (Holland, 2002).

succession of volcanic-sedimentary rocks recording the time of emergence of an aerobic world.

Core Archive and Drilling Information System (DIS)

All cores were transported to the Geological Survey of Norway (NGU) in Trondheim for curation and archiving. All technical and geological data gathered during the drilling operations and through the archiving process have been catalogued using the Drilling Information System (DIS, see Web Links) developed by ICDP. During the project, the functions of this software have been continuously updated to meet the specific FAR-DEEP needs. The archive process began in March and was completed by December 2008.

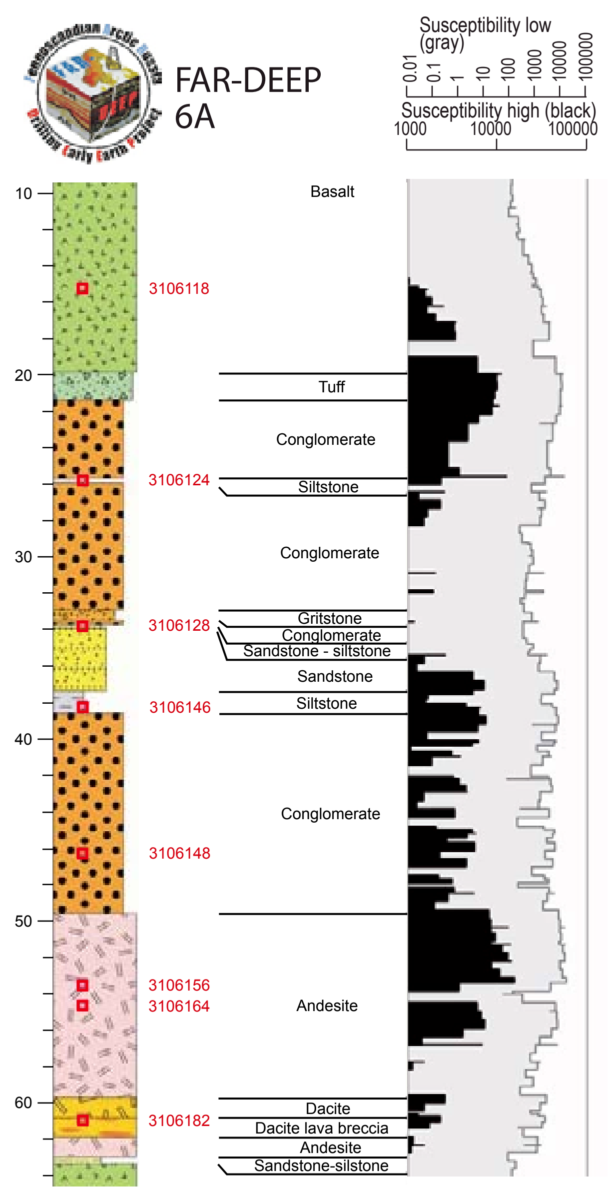

Figure 3. Example of a drillhole log with position of archive samples (red squares) and their numbers. Magnetic susceptibility data are plotted alongside.

At the NGU's core repository the archive process included (1) high-resolution photography of core in boxes, in dry and wet conditions, (2) magnetic susceptibility measurements of full core at ~20-cm intervals, (3) core splitting by sawing, (4) image scanning and photography of split core, (5) detailed lithological description, (6) and routine sampling with ~7-m spacing for general geochemical and petrographic characterizations of the rocks. The archive sample set consists of 554 specimens that have been analyzed for whole-rock major and trace elements, carbonate composition, abundance of C and S, and thin sections have been made from them at the NGU laboratory. Selected specimens from the archive set have been analyzed for S isotopes of sulfides, C- and N-isotopes of the organic matter, and C-, O-, and Sr-isotopes of carbonates by the FAR-DEEP international team of researchers. All documentation obtained during the archiving process and general geochemical profiles of cores (Fig. 3) were made available for the FAR-DEEP partners on the Internet prior to core sampling in Trondheim from March to April 2009.

"Coring" through Major Paleoproterozoic Events and Paleoproterozoic Reference Sections

The FAR-DEEP cores of sedimentary and volcanic formations in the stratotype areas of the Pechenga and Imandra/Varzuga Greenstone Belts and the Onega Basin (Fig. 1) record the global events of the APT (Figs. 4 and 5).

Change in fractionation of sulfur isotopes. Several lines of evidence imply Earth's earliest atmosphere shifted from being anoxic to oxic between 2500 Ma and 2000 Ma (GOE, Fig. 2). The processes driving this shift, as well as their timing and duration, remain enigmatic. Appearance of 'red beds' and sulfates in the stratigraphic record is among the most compelling evidence reflecting the change to oxic conditions. Additional support for the oxygenation has been gained from recent work on S-isotopes that have shown the presence of mass-independently fractionated (MIF) S-isotopes in rocks older than 2360 Ma and disappearance of such a signature thereafter (Bekker et al., 2004; Hannah et al., 2004; Guo et al., 2009). The disappearance of MIF S-isotopes has been typically attributed to the oxygenation of the atmosphere and related change in photochemical reactions, but other processes have also been proposed (Watanabe et al., 2009). FAR-DEEP's drillhole 1A intersected a sequence of marine shales (Fig. 6A) and sandstones deposited prior to 2442 Ma (Fig. 4). These 2442-Ma rocks show a transition from MIF to mass-dependently fractionated sulfur isotopes (Reuschel et al., 2008); thus, they offer new constraints on the S-isotope cycle at the dawn of the GOE. Moreover, isotope geochemistry of marine carbonate rocks interbedded with shales may represent a robust proxy for the global carbon cycle prior to the Huronian-age glaciation (Young et al., 2001).

Huronian-age global glaciation. The rapid onset of global glaciation(s) from otherwise climatically invariant conditions at around 2320 Ma (age constraint from South Africa, Hannah et al., 2004) is another significant environmental event during the APT. The triggering mechanisms remain poorly understood (Evans, 2003) and several models have been advanced to explain them (Melezhik, 2006; Claire et al., 2006). In the Imandra/Varzuga Greenstone Belt, drillhole 3A intersected Huronian-age diamictites (Fig. 6B). These are overlain by spinifex-textured komatiites (Fig. 6C) and underlain by Sr-rich limestones, all resting on felsic volcanic rocks. This setting offers unique opportunities for reconstructing paleolatitudinal positions, a geochemical record of seawater Sr- and C-isotopic composition and geochronology.

Unprecedented perturbation of the global carbon cycle. The largest positive excursion of $\delta^{13}C$ known in Earth's history as recorded in sedimentary carbonates—termed the Lomagundi-Jatuli Event—is one of a series of prominent Paleoproterozoic environmental events whose interrelationships remain intriguing and only partially resolved (Melezhik et al., 2007). At present, no consensus exists on the causative mechanism(s) responsible for the Lomagundi-Jatuli Event (Bekker et al., 2001, 2003a; Hayes and Waldbauer, 2006). The possible role of local factors in amplification of a global signal remains unresolved (Melezhik et al., 1999; Bekker et al., 2003a, 2003b; Aharon, 2005). Drillholes 4A, 5A, 10A, 10B, and 11A intersected ^{13}C-rich carbonates of the Lomagundi-Jatuli Event (Fig. 6D) in three different depositional and paleotectonic settings. Drillholes 8A and 8B cored carbonates (Fig. 6E) that post-date the Lomagundi-Jatuli Event. The study of all these cores will help to understand onset, duration, and causes of this unique perturbation of the global carbon cycle.

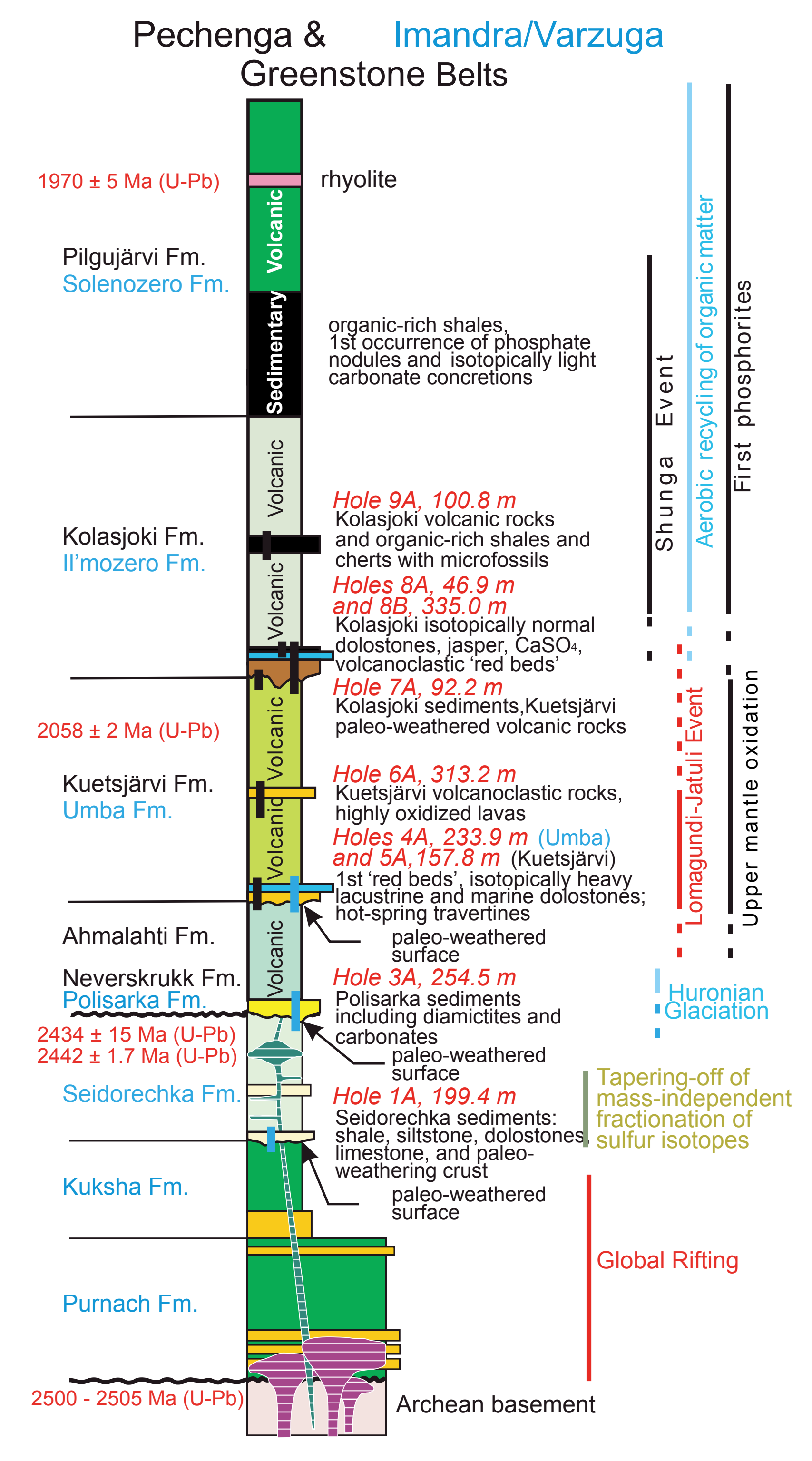

Figure 4. Composite (~10,000-m-thick) and simplified Paleoproterozoic section for the Pechenga and Imandra/Varzuga Greenstone Belts linked to major paleoenvironmental events. Radiometric dates from bottom to top are from Amelin et al. (1995), Melezhik et al. (2007), and Hanski (1992). The Pechenga Belt stratigraphy is shown in black-face letters, and the drilled holes by vertical black lines; features for the Imandra/Varzuga Belt are in blue. The number of the drillhole and its depth are shown in red-face letters; this is followed by text briefly describing rock lithologies intersected by the hole.

Oxidized ocean – abundant Ca-sulfates. Progressive oxygenation of Earth's surface environments resulted in increased sulfide oxidation during continental weathering and a concomitant increase in the concentration of marine sulfate (Guo et al., 2009). However, to date, available esti-mates of marine sulfate reservoir size remain controversial (Kah et al., 2004; Melezhik et al., 2005b),. Several FAR-DEEP drillholes (5A, 8A, 8B, 10A, 10B, 11A) successfully targeted sedimentary formations that contain seawater sulfates. Pseudomorphs after gypsum and anhydrite, with relicts of primary minerals, have been documented in great abundance (Fig. 6F, 6G). Detailed mineralogical and isotopic studies to decipher their environmental significance are in progress and will help constrain the oxygenation history.

Ferric iron-rich volcanic rocks: upper mantle oxidizing event vs. secondary overprint by oxidized groundwaters. Was the rise of atmospheric oxygen levels related to increased dioxygen due to evolution of oxygen-producing organisms, or was it controlled by a decrease in oxygen sinks (Kump, 2008)? One hypothesis is that a predominant sink for oxygen in the Archean era was abruptly and permanently diminished during the APT (Kump and Barley, 2007), but the overall cause of the GOE remains unresolved. Approximately 2060-Ma-old volcanic rocks (Fig. 6H, 6I) in the Pechenga Greenstone Belt have high Fe^{3+}/Fe_{total} ratios (average=0.37) which are in sharp contrast to the majority of underlying and overlying volcanic units. The FAR-DEEP drillholes 4A and 6A recovered more than 300 meters of such highly oxidized lavas (Fig. 6I). This anomaly may represent evidence either for relatively oxidized mantle material (e.g., recycled banded iron formations) or a large-scale alteration of Earth's surface by oxidized meteoric and/or groundwaters.

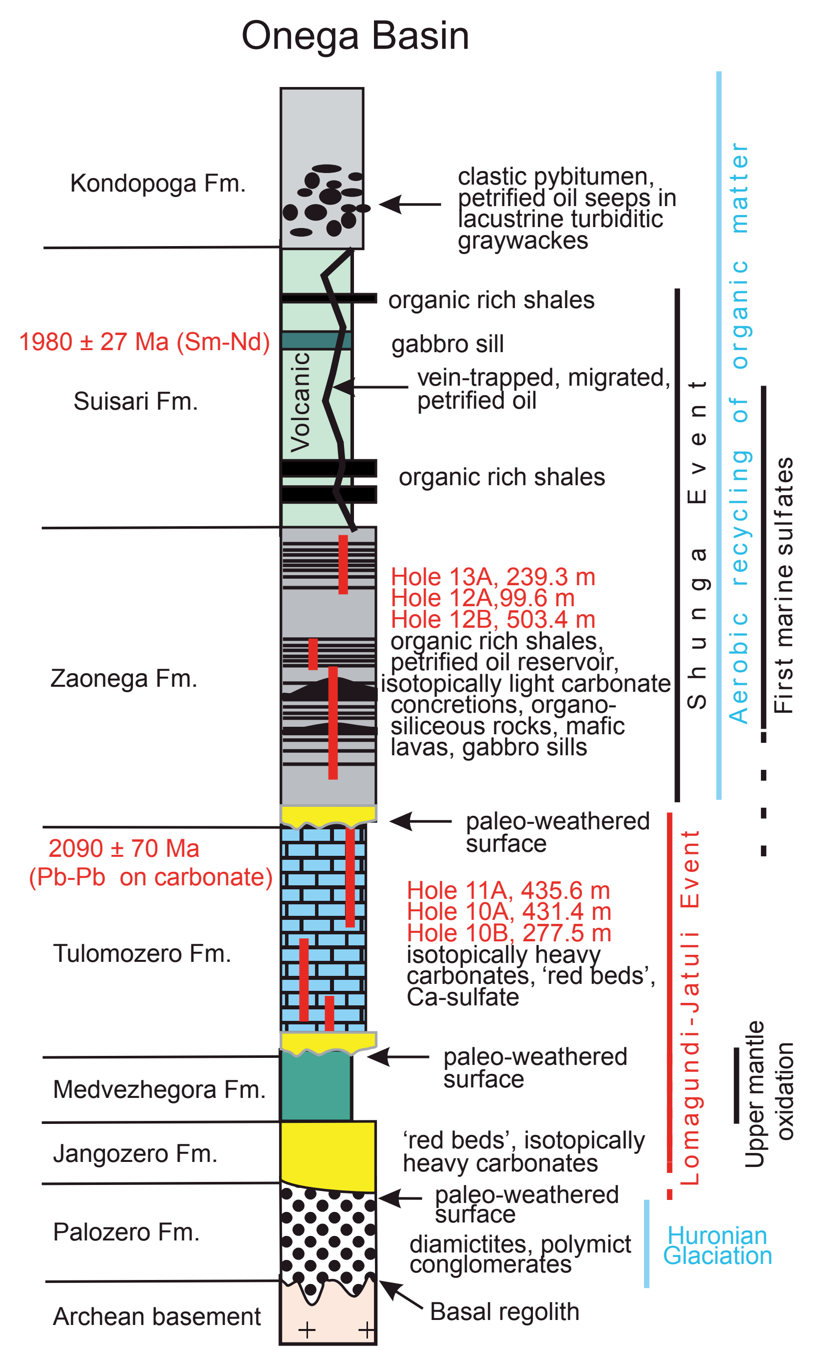

Figure 5. Composite (~5000-m-thick) and simplified Paleoproterozoic section for the Onega Basin linked to major paleoenvironmental events. Radiometric dates from bottom to top are from Ovchinnikova et al. (2007) and Pukhtel et al. (1992). Vertical red lines show the position of the drillholes. The number of the drillhole and its depth are shown in red-face letters; this is followed by text briefly describing rock lithologies intersected by the hole.

Subaerial and subaqueous hydrothermal systems. Two types of compositionally different hydrothermal products have been documented in the FAR-DEEP drillcores. The first type is represented by iron oxide-silica-dominated rocks (jasper). This appears in a large variety of occurrences in the FAR-DEEP cores, including numerous amygdales (Fig. 6I), veinlets and veins in volcanic rocks (Fig. 6J), siltstone- and dolostone-hosted layers, beds, and feeder-veinlets in dolostones and siliciclastic sediments (Fig. 6K), and redeposited clasts in fluvial, deltaic and marine sediments. The occurrences of jasper thus represent a complex history of fluid migration and redox alteration in a suite of processes linked to the GOE.

The second type of hydrothermal products is travertine (Fig. 6L), occurring in great abundance as thin crusts and feeder-veinlets in ^{13}C-rich lacustrine dolostones (Fig. 4, Kuetsjärvi Fm). These oldest ever documented travertines may signify a radical change in Earth surface environment to one allowing the precipitation of hydrothermal carbonates in subaerial conditions. Drillcores from holes 5A, 6A, 7A, 8A, and 8B provide excellent material for studying the complex 'iron story' around the GOE, as well as the earliest known travertine-precipitating hydrothermal systems.

Revolution in biological cycling of phosphorous and organic matter. Post-Lomagundi-Jatuli deposits (2000 Ma) record the first known appearance (if siderite in banded iron formations is excluded) of

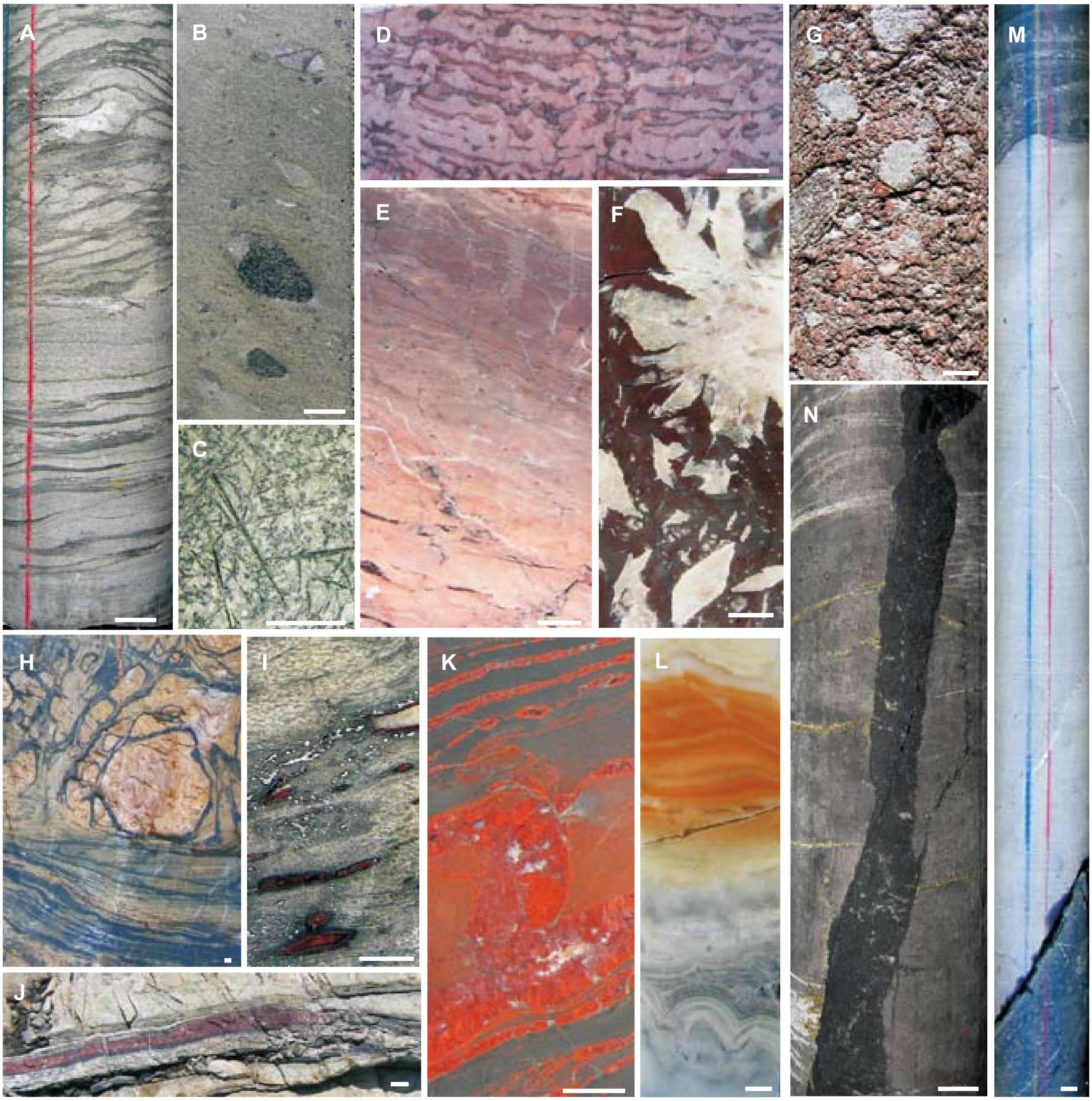

Figure 6. Major Paleoproterozoic paleoenvironmental events documented in the FAR-DEEP cores and adjacent outcrops. [A] Sandstone-shale from drillhole 1A with tidal bedding formed at the start of the GOE. [B] Diamictite accumulated during the Huronian-global glaciation; drillhole 3A. [C] Spinifex-structured komatiites overlying the diamictites; drillhole 3A. [D] Jatuli-age, red, stromatolitic, ^{13}C-rich, dolostone recording the unprecedented perturbation of the global carbon cycle during the Lomagundi-Jatuli Event; red color is indicative of oxic environment associated with GOE; drillhole 10A. [E] Post-Lomagundi-Jatuli, pink, isotopically "normal", dolostone recording the recovery from the perturbation in the global carbon cycle; drillhole 8B. [F] Dolomite-quartz pseudomorphs after gypsum rosette and crystals emplaced in red clay; abundant Ca-sulfates suggest a significant ocean sulfate reservoir; drillhole 10B. [G] Dissolution of anhydrite and halite resulted in porous appearance of matrix-supported conglomerate; drillhole 11A. [H] ~2060-Ma weathering surface imprinted in hematite-cemented (black) felsic lava-breccia in vicinity of drillhole 7A; this is indicative of oxic meteoric and ground waters during the GOE. [I] Jasper-filled amygdales (dark red) in oxidized felsic lava from drillhole 6A; this may record an upper mantle oxidizing event. [J] Jasper vein in dacitic lava near drillhole 7A; such veins are truncated by overlying sediments and are the product of subaerial, syn-volcanic hydrothermal activity. [K] Greywacke-hosted jasper layers and beds precipitated from sub-aqueous hydrothermal system; drillhole 8B. [L] The earliest known travertines on Earth from drillhole 5A. [M] ^{13}C-depleted carbonate concretion incorporating carbon derived from oxic recycling of the organic matter; drillhole 12B. Bar scales in all photos are 1 cm. [N] Pyrobitumen vein representing a 2000-Ma oil migration pathway; drillhole 12A. These units contain both mass-independent and mass-dependent fractionation of sulfur isotopes.

diagenetic carbonate concretions significantly depleted in ^{13}C (Fallick et al., 2008). They are varied in size and composition and abundant in sedimentary successions <2000 Ma where they are associated with other diagenetic products such as phosphorites, all of which are seemingly absent in older rocks. Thus, these suggest a major change in the diagenetic mineralization of organic matter, perhaps reflecting increased rates in dissimilatory sulfate reduction (Canfield and Raiswell, 1999). This in turn suggests an elevated concentration of interstitial phosphate. Drillholes 9A, 12A, 12B, and 13A recovered hundreds of meters of cores containing abundant carbonate nodules (Fig. 6M) and carbonate-associated phosphorites, which allow us to address the causes of the emergence of 'modern-style' recycling of organic matter, are and the factors that control the formation of the oldest known phosphorites.

Supergiant petroleum deposits. The most remarkable accumulation of organic-matter-rich sediments and generation of petroleum in the Precambrian took place at around 2000 Ma ago in the aftermath of the Lomagundi-Jatuli Event (Melezhik et al., 2009). This is known as the Shunga Event. The causes (e.g., high productivity or anomalous preservation) of such unprecedented global accumulation of organic-matter and pervasive oil generation remain unknown. In the type area at Shunga, three FAR-DEEP drillholes (12A, 12B, 13A) intersected several hundred meters of organic matter-rich source rocks, a uniquely preserved oil migration pathway (Fig. 6N), a petrified supergiant oilfield, and several bodies of enigmatic organo-siliceous rocks containing up to 40 wt% organic carbon. More than 100 archive samples have already been analyzed for major and trace elements as well as for S- and C-isotopes of sulfides, organic matter and associated carbonates, and they indicate a complex geochemical evolutionary pattern. These data, together with the results of forthcoming studies on biomarkers and structural, isotopic, and trace element characteristics of organic matter, will enable several fundamental problems associated with the Shunga Event to be addressed.

International Sampling and Acknowledgements

The drilling operations were carried out by a Finnish operator, whereas all logistical support was provided by the Russian State Company "Mineral" from St. Petersburg, Russia. Selected specimens from the archive set have been analyzed by partners at the Westfälische Wilhelms-Universität, Münster, Germany (H. Strauss), the Scottish Universities Environmental Research Center, Glasgow, Scotland (A.E. Fallick), the Pennsylvania State University, U.S.A. (L.R. Kump), and the Institute of Precambrian Geology and Geochronology, St. Petersburg, Russia (I.M. Gorokhov). The NGU, Center of Excellence in Geobiology at the University of Bergen in Norway, and the Institute of Geology at the Karelian Research Center in Petrozavodsk, Russia provided resources for the archiving work. In March–April 2009, the NGU provided its facilities and logistical support for an international sampling campaign. Samples have been collected either directly by scientists who have examined the core in Trondheim or by the NGU's staff upon sample requests submitted by FAR-DEEP partners. More than 5500 samples have been collected from cores, and they are being prepared for various analyses and experiments. Scientists from thirteen countries have applied for research grants from various funding agencies to complete studies of the FAR-DEEP cores. Currently, five PhD students from Finland, Germany, and Norway are involved in the FAR-DEEP research program. Four postdoctoral projects in Finland, Great Britain, and Norway have been financed by national funding agencies. A large group of scientists from the U.S.A. has received support from the U.S. National Science Foundation and NASA. Several research groups from Australia, Belgium, Czech Republic, Estonia, and Russia have also been successful in obtaining research grants.

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and the FAR-DEEP Scientists

Web Links

http://far-deep.icdp-online.org (Internal Data FARDEEP)
http://www.icdp-online.org/front_content.php?idart=1962

New Integrated Data Analyses Software Components

by Ronald Conze, Frank Krysiak, Josh Reed, Yu-Chung Chen, Hans-Joachim Wallrabe-Adams, Colin Graham and the New Jersey Shallow Shelf Science Team, Volker Wennrich and the Lake El'gygytgyn Science Team

doi:10.2204/iodp.sd.9.08.2010

Introduction

Data management in scientific drilling programs such as the Integrated Ocean Drilling Program (IODP), the International Continental Scientific Drilling Program (ICDP), and the Antarctic Drilling Program (ANDRILL) performs two functions: firstly, the capture of drilling and scientific data during an expedition, and secondly, the long-term storage and dissemination of these data. Here we describe the progress in linking data management with stand-alone data capture and visualization applications. This provides a two-way flow of data between the database and the applications, and a more integrated data environment for scientists. The new system has been tested, so far, with cores from the IODP Expedition 313 New Jersey Shallow Shelf and the ICDP Lake El'gygytgyn Drilling Project.

The Components

1. The Expedition Drilling Information System (ExpeditionDIS) is used for ICDP lake drilling projects and IODP-MSP expeditions in a two-phase data capture process, at the drill site during the drilling operation and in one or more laboratories during the post-drilling phase (Conze et al., 2007). It is based on a relational database using mainly digital forms for the data input.
2. PSICAT, the Paleontological Stratigraphic Interval Construction and Analysis Tool, is a stand-alone, Java-based graphical editing tool for creating and viewing core description diagrams (http://dev.psicat.org/) that can be used in the field as well as in a laboratory environment.
3. Corelyzer as part of CoreWall (http://www.corewall.org/) is a scalable, extensible visualization tool, developed to enhance the study of geological cores. The strength of Corelyzer is the ability to display large sets of core imagery, with multi-sensor logs and annotations. Plugins can be developed to provide additional data visualization functionality.
4. Correlator, another CoreWall product, is an interactive workstation software product for displaying and depth-shifting/merging data from multiple cores and/or downhole geophysical logging data.

The Concept

The idea is to combine the advantages of all these stand-alone tools into an interoperable configuration.

The link between the ExpeditionDIS, PSICAT, and Corelyzer is realized by a Common Exchange Format (Fig. 1) using XML notation. The general workflow starts with the export of all relevant primary data for core recovered from a drill hole from the ExpeditionDIS in the Common Exchange Format, which can then subsequently be imported by PSICAT and/or Corelyzer. A Common Exchange Format file contains the corresponding driller depths and file paths for core section images as well as any existing lithological visual core description data for each core section, and other corresponding data sets such as petrophysical (e.g., from Multi Sensor Core Logging, MSCL) data.

1. By importing the ExpeditionDIS data as Common Exchange Format, PSICAT generates a visual core description (VCD) form for each core section. Existing VCD data can be modified, and new data can be added using the graphical functionality of PSICAT. The new or modified data can be written back to the

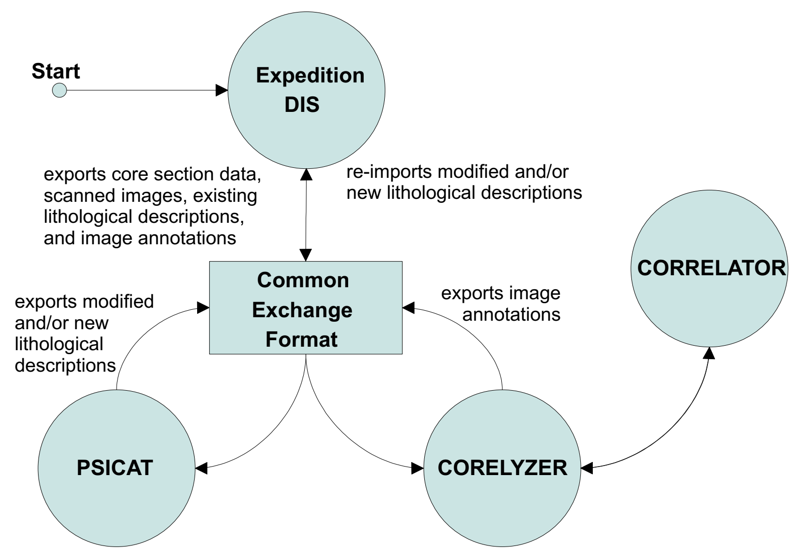

Figure 1. Conceptual diagram showing data exchange between the components (Figure credit by R. Conze).

Figure 3. Corelyzer station at the IODP Exp. 313 New Jersey Shallow Shelf onshore science party at MARUM (University of Bremen). This station was fed continuously with scanned images and MSCL data of new core sections as they were added to the ExpeditionDIS. In conjunction with Correlator, this station was used for correlation between sites using lithological features and/or logging data. (Photo by H. Ando, Ibaraki University)

ExpeditionDIS via the Common Exchange Format file. Upon selecting a subset of core sections or all core sections for a drill hole, a non-editable, continuous sequence, scaled to the driller depth, is displayed.

2. By importing a Common Exchange Format file, Corelyzer reads in all core images and corresponding optional logging data (Fig. 2). The utilization of an existing PSICAT plugin will allow visualization of the lithological units graphically beside these scanned images and log data. The user can add annotations to the images, which are added to the Common Exchange Format file and then exported for use by the other tools.
3. By re-importing the Common Exchange Format data generated by PSICAT, and Corelyzer, the ExpeditionDIS can store all modified or new lithological data.
4. By connecting Correlator, Corelyzer can control visualization and core depth adjustments in runtime using socket commands. It will allow users to utilize rich features in high-resolution core images to generate composite and spliced depth scales. This feature allows more fine-grained interactive stratigraphic correlations.

Benefits and Outlook

The two test beds demonstrated that the synergetic integration of ExpeditionDIS, PSICAT and Corelyzer is beneficial and enhances the capabilities of the individual stand-alone systems. The ExpeditionDIS and its relational database provide the full documentation of all recovered cores and sections including consistent driller depths and the corresponding scanned images in different grades of resolution. Neither PSICAT nor Corelyzer provides any tools to capture these important primary data, but both need these data as input for generating lithological visual core descriptions and visualization of the scanned images of the core sections and related logging data. In conjunction with Correlator it will be possible to import the depth adjustment tables by ExpeditionDIS using the same Common Exchange Format so that any data can be output on the same composite or spliced depth scales.

Upcoming scientific drilling expeditions of ICDP and ECORD/IODP will provide further test beds for consolidation and development of such features.

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Automatic Slide-Loader Fluorescence Microscope for Discriminative Enumeration of Subseafloor Life

by Yuki Morono and Fumio Inagaki

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Introduction

The marine subsurface environment is considered the potentially largest ecosystem on Earth, harboring one-tenth of all living biota (Whitman et al., 1998) and comprising diverse microbial components (Inagaki et al., 2003, 2006; Teske, 2006; Inagaki and Nakagawa, 2008). In deep marine sediments, the discrimination of life is significantly more difficult than in surface sediments and terrestrial soils because buried cells generally have extremely low metabolic activities (D'Hondt et al., 2002, 2004), and a highly consolidated sediment matrix produces auto-fluorescence from diatomaceous spicules and other mineral particles (Kallmeyer et al., 2008). The cell abundance in marine subsurface sediments has conventionally been evaluated by acridine orange direct count (AODC; Cragg et al., 1995; Parkes et al., 2000) down to 1613 meters below the seafloor (mbsf) (Roussel et al., 2008). Since the cell-derived AO signals often fade out in a short exposure time, recognizing and counting cells require special training. Hence, such efforts to enumerate AO-stained cells from the subseafloor on photographic images have been difficult, and a verification of counts by other methods has been impossible. In addition, providing mean statistical values from low biomass sedimentary habitats has been complicated by physical and time limitations, yet these habitats are considered critical for understanding the Earth's biosphere close to the limits of habitable zones (Hoehler, 2004; D'Hondt et al., 2007).

Here we report recent developments on the automatic cell count system based on our recently published new cell detection and enumeration method that discriminates the SYBR Green I(SYBR I)-stained cells from the background fluorescent signals, called SYBR-SPAM (SYBR-Stainable PArticulated Matter; Morono et al., 2009). We integrated an automatic slide loader and an LED light-camera monitoring system for high-throughput and high-resolution counting operation.

Principle of Discriminative Detection

SYBR-I or SYBR-II has been considered a more effective fluorescent dye for cell enumeration in sediments than AO due to its higher fluorescent intensity and sensitivity to nucleic acids (Weinbauer et al., 1998; Lunau et al., 2005; Engelen et al., 2008). However, we found non-autofluorescent SYBR-I-stainable particulate matter (SYBR-SPAM) in heat-sterilized control sediments treated at 450°C for 3 hours (Morono et al., 2009). We also found that when SYBR-I bound to SYBR-SPAM the SYBR-I spectra shifted to longer wavelengths (Fig. 1A), and that the spectra can be distinguished from cell-derived green fluorescence under the observation of a long-pass filter of cut-off wavelength 510 nm (Fig. 1B). To discriminate the cell-derived fluorescent signal more precisely, we obtained microscopic images using band-pass filters at 528/38 and 617/73 nm (center wavelength/bandwidth) that separated the green and red components of SYBR-I fluorescence (Fig. 1C, D). We divided the fluorescent intensity of green by that of the red images to obtain relative intensity profiles of green/red fluorescence, in which cell-derived fluorescence was successfully discriminated as bright signals, whereas SYBR-SPAM and other background signals were entirely eliminated (Fig. 1E).

Sample Preparation Protocol

A standard sample preparation scheme is shown in Fig. 2. Fifty microliters of sediment slurry (10% [v/v] sediment in ethanol-PBS solution) fixed in 2% paraformaldehyde is mixed with 850 µL of 3% [wt/v] NaCl solution and sonicated at 20 W for 1 min on ice using an ultrasonic homogenizer (Model UH-50, SMT Co. Ltd., Tokyo). The sonicate is then mixed with 100 µL of 10% [wt/v] hydrofluoric acid (HF) and incubated for 20 min at room temperature. This HF treatment has been shown to effectively decrease the number of SYBR-SPAM especially in shallow subseafloor sediments, while intracellular DNA is negligibly affected (Morono et al., 2009). Then, up to 700 µL of the mixture is directly filtered through a 0.22 µm-pore size black polycarbonate membrane without centrifugation. The final sediment volumes on the filter are up to 3.5 x 10^{-3} cm^3. To eliminate potential carbonate particles and/or precipitates, the membrane is treated with 1 mL of 0.1 M HCl for 5 min on the filtration device. The membrane is then washed with 5 mL of TE buffer (10 mM Tris-HCl, 1.0 mM EDTA, pH 8.0), and roughly 2 x 10^8 fluorescence microsphere beads (Fluoresbrite Bright Blue Carboxylate Microspheres [BB beads], 0.5 µm, Polysciences, Inc., Warrington, Pa.) are used for focus adjustment (Morono et al., 2009). After air drying, one-fourth of the membrane is placed on the filtration device again, then stained with SYBR-I staining solution (1/40 [v/v] SYBR-I in TE buffer). The stained filter is finally mounted on a glass microscope

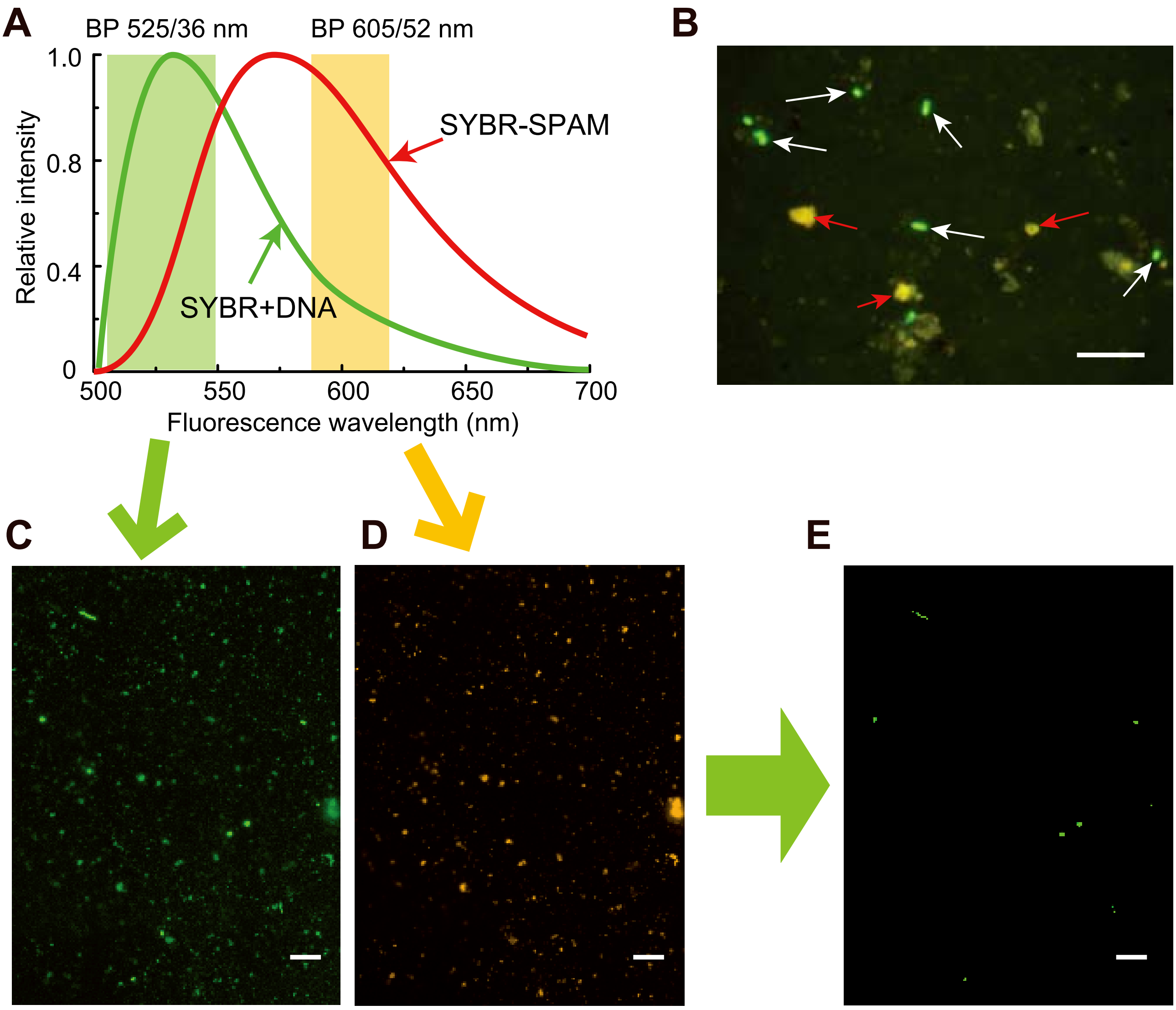

Figure 1. Difference of SYBR-I fluorescence spectrum with intracellular DNA or SYBR-SPAM, and discrimination of cell-derived SYBR Green I fluorescence from background signals using image analysis. [A] Spectrum patterns show "red shift" of SYBR-I fluorescence. When SYBR-I binds to SYBR-SPAM (red line), fluorescence spectra shift to longer wavelengths than SYBR-DNA complex (green line). Green and orange shaded areas show the wavelength range of 525/36 and 605/52 (nm of center wavelength/bandwidth) band-pass filters, respectively. [B] Examples of fluorescence-producing cellular and non-cellular objects stained with SYBR-I. Red arrows, yellowish SYBR-SPAM. White arrows, green *E. coli* cells. The image was obtained using a long-pass filter of cut-off wavelength 510 nm. [C to E] Image analysis to distinguish cell-derived SYBR-I signals from SYBR-SPAM in natural marine sediments (core 1H-1 of Site C0006 Hole E in the Integrated Ocean Drilling Program Exp. 316). Fluorescence microscopic images taken using band-pass filters of 525/36 [C] and 605/52 [D]. Relative intensity profiles of green/red fluorescence [E] show only cell-derived fluorescence signals without background fluorescence. Bars: 10 µm.

slide with 3–5 µL of mounting solution (1:2 mixture of VECTASHIELD mounting medium H-1000 and TE buffer).

The Slide Handler-Equipped Automatic Fluorescence Microscope System

The images are automatically acquired with a fluorescent microscope system (Fig. 3A) that consists of a basic microscope (BX-51, Olympus), an automatic slide handler (LEP Slide Handler System, Ludl Electric Products, Ltd.), illumination with LED Array Modules (LAMs) of 400 nm and 490 nm (precisExcite, CoolLED, Ltd.), an emission filter wheel (Ludl Electric Products, Ltd.), and a cooled CCD camera (ORCA-AG, Hamamatsu Photonics K.K.) All units are software controlled (MetaMorph 7.5, Molecular Devices). Up to 50 slides of samples can be set in two magazines of the slide handler (Fig. 3B). To keep the sample in good condition for a long time (depending on the scanning area but at least 30 min per sample, i.e., 25 h duration to process all 50 slides), the whole system is put in a dark cooled (15°C) chamber. In addition, we also installed a digital camera to monitor the system without opening the door of the chamber (Fig. 3C, D). LED illumination allows for (i) an instant on/off switch and wavelength change without damage to the lamp source, (ii) a prolonged lifetime in comparison to mercury lamps, and (iii) negligible heating during operation.

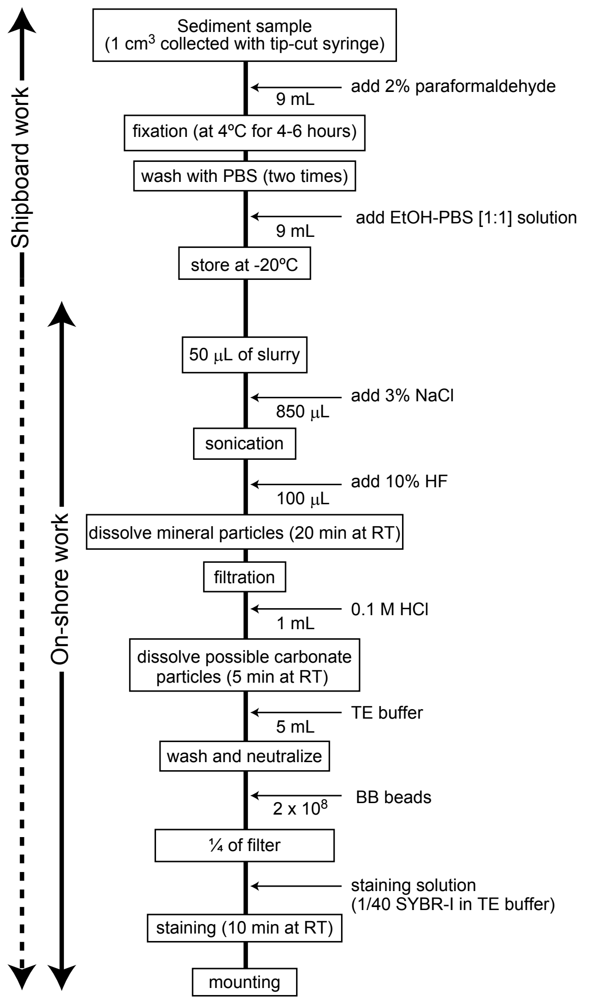

Figure 2. Flow diagram of standard sample preparation protocol. Up to 3.5 x 10^{-3} cm^3 of sediment is mounted on the slide

The microscopic imaging is controlled with the software in a "Scan Slide" function that scans a user-defined area of the sample while adjusting the focus on each plane. As the deviation of the slide thickness was comparably large (0.8–1.0 mm), we programmed a wide-focus adjustment macro searching a focus position through a range of 120-µm Z-positions before scanning each slide. After the wide-focus adjustment, the image acquisition sequence with "Scan Slide" proceeds as follows: (i) scan Z-position under 400 nm excitation and 455/50 nm emission filter to focus on BB beads, (ii) fix Z-mortar and acquire bead image, (iii) change excitation to 490 nm and emission to 525/36 nm (green), (iv) acquire cell image, (v) change emission to 605/52 nm (red), and (vi) acquire background image.

The images obtained are analyzed with the macro in the following way. The fluorescence intensity of each pixel in the green image is multiplied by 100 and divided by that of the red image at the same location. The resulting images showing the ratio of the relative intensity of green/red fluorescence were smoothed by median filtering (3 x 3 pixel square), and watershed lines were drawn to separate cells in close proximity to each other. Based on *Escherichia coli* images in control sediments and cellular signals in natural sub-seafloor sediments, we set the threshold value of relative fluorescence at 110 for automatic cell enumeration. Under these threshold conditions, non-specific signals in heat-sterilized sediments as well as on blank filters resulted in a null count. Figure 4 shows the effect of the HF treatment and the image analysis. Counting performed without the modification results in a serious overestimation (100 times higher) of the biomass.

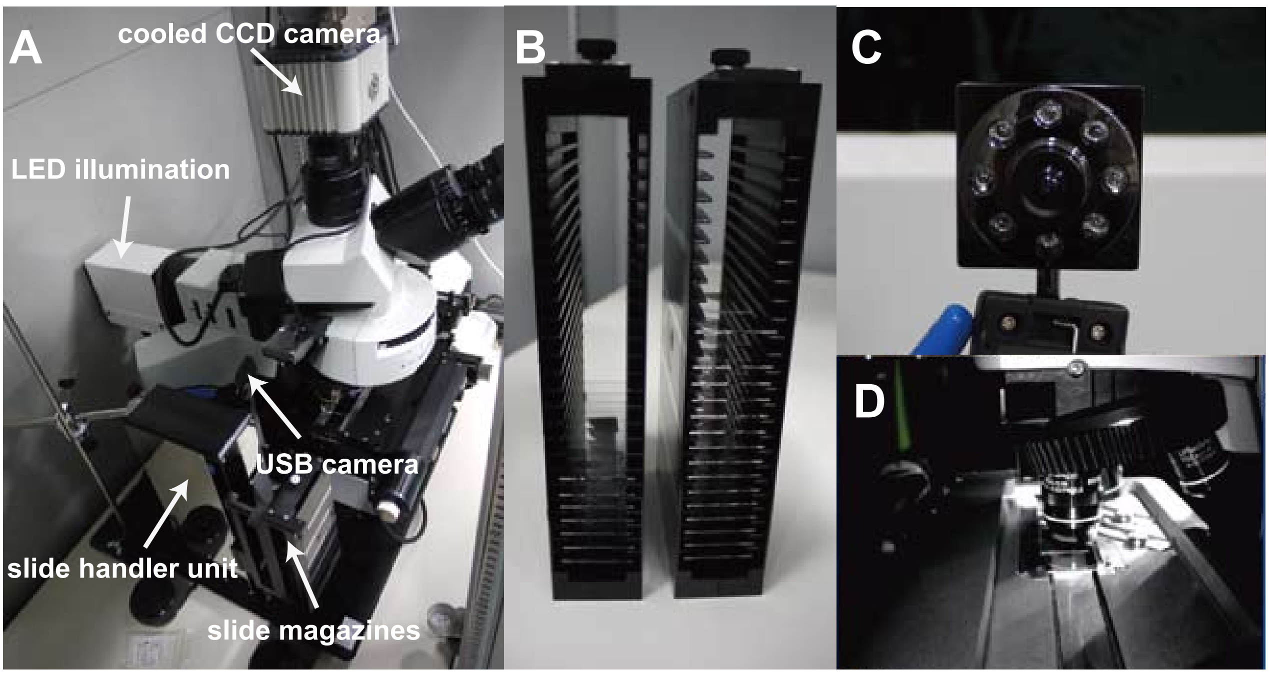

Figure 3. Newly constructed automatic microscopic system with slide handler. [A] Overview of the system. All the units are operated in a dark and cool (15°C) chamber. [B] Slide magazines capable of carrying 25 slides each. [C] USB-connected monitoring camera with infrared LED. [D] The system is monitored without opening the door of the chamber.

Detection Limit of Life Forms and Future Improvement

The lower limit of detection of DNA-containing lifeform signatures (i.e., Archaea, bacteria, and viral components) can only be determined with a maximum load of samples on the filter and a prolonged time for counting. In our examination, 3.5 x 10^{-3} cm^3 was found to be the maximum load on the filter of 2.5 cm^2 active filtration area. Although we tried to load more on the filter, sediment particles piled up and resulted in focus failure throughout the image field. The maximum load corresponds to 5.1 x 10^{-5} cm^3 of sediment for a field with a 40x objective lens. According to Kallmeyer et al. (2008), three times more cells are needed in source sediment for detecting at least one cell with 95% probability. The detection limit with one image field is therefore 5.9 x 10^6 cells cm^{-3}. By considering the time (roughly 8 sec) required for taking one field of image with our system, we can obtain a comparison of detection limit vs. required acquisition time as shown in Table 1. Currently we have already tried and succeeded in analyzing a quarter of the filter and counting down to 3.4 x 10^3 cells cm^{-3} in a few hours. To lower the limit further, the required time will increase inversely (Table 1). A practical limit would be less than 100 hours of analysis, which corresponds to a detection limit of 1.3 x 10^2 cells cm^{-3}. For even lower biomass habitats, a brief centrifugation at 100 x *g* (Lunau et al., 2005) or a density gradient separation (Kallmeyer et al., 2008) that reduces mineral particles enables larger amounts of sediment to be placed on the filter and extends the detection limit by 10- to 1000-fold. However, the recovery rate depends on natural cell densities and field conditions (Morono et al., 2009) and may sometimes cause serious loss of the cells. The use of a centrifugation step should be carefully considered, and cell concentration should be described as the minimal value in such a case. The system presented here will be useful for primary microbiological onboard data if deployed on scientific drilling platforms. In addition, such a separation technique will open the door for the application of other analytical tools that detect activities of life in low biomass habitats using nanoscale secondary ion mass spectrometry (NanoSIMS; Kuypers and Jørgensen, 2007). Hence, the direction of future technical developments should be towards both the detection of life components with specific signals (e.g., deep UV excitation, see Bhartia et al., 2008) and the detection of activities and metabolic functions of deep subseafloor life.

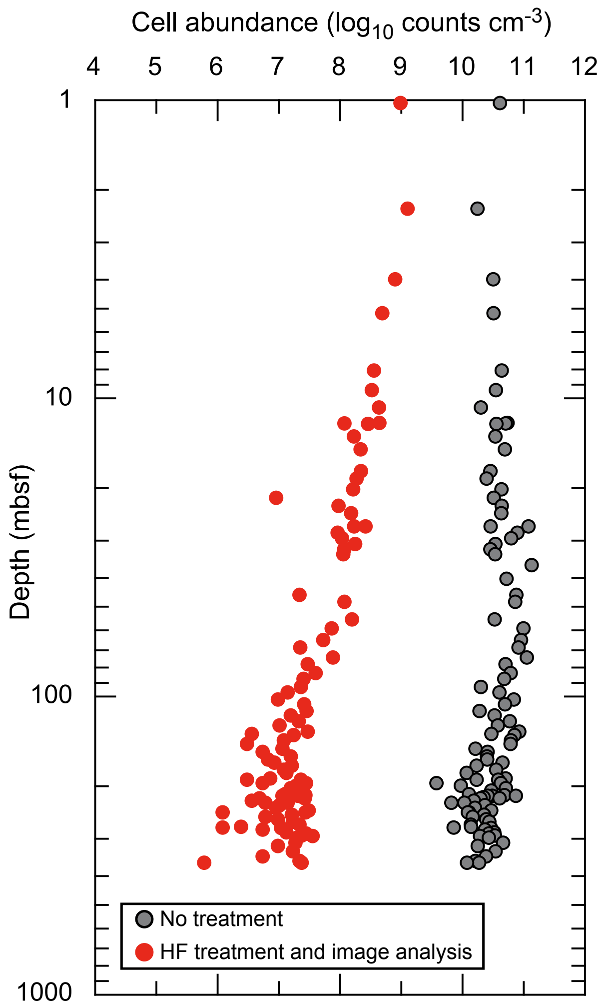

Figure 4. SYBR-I counts of fluorescence signals in sediments collected from offshore of the Shimokita Peninsula of Japan during the *D/V Chikyu* shakedown expedition CK06-06. Gray dots: no acid wash and manual (human-eye) cell counting results without image analysis (seriously overestimated). Red dots: computer-based cell counts in HF-washed sediment samples (modified from Morono et al., 2009).

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Table 1. Correlation of the lower detection limit and the corresponding time required for obtaining images, amount of sediment, number of images, and number of filters.

Lower limit of detection (cells cm^{-3})	Required time (hrs)	Required sediment volume (cm^3)	Number of image fields	Area of analysis (cm^2)	Number of required filters
1.04x10^4	1	0.000287	450	0.163	1
1.04x10^3	10	0.00287	4,500	1.63	1
1.04x10^2	100	0.0287	45,000	16.3	7
1.04x10^1	1000	0.287	450,000	163	66
1.04	10000	2.87	4,500,000	1630	652

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High-Precision Orientation of Three-Component Magnetic Downhole Logs

by Christopher Virgil, Andreas Hördt, Torsten Klein, Jochem Kück, Martin Leven, and Erich Steveling

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Introduction

The possible benefits of measuring the magnetic flux density in three components continuously along a borehole have been recognized a long time ago by researchers who developed models and interpretation schemes for 3-component magnetic borehole data (Parker and Daniell, 1979; Gallet and Courtillot, 1989).

Common borehole methods provide data not allowing for an orientation with respect to a global reference, since this requires a highly accurate orientation system independent of the magnetic measurements. A first attempt to obtain the orientation of the sonde was made by Bosum et al. (1988) using a mechanical gyro and accelerometers. However, at that time the data quality of the gyro did not allow for a continuous 3-component measurement. Steveling et al. (2003) provide an example from the Hawaii Scientific Drilling Project (HSDP) drill hole, where directional information of magnetization was used to separate massive lavas from hyaloclastites. However, their directional analysis was limited to the inclination because information on the tool rotation around the vertical axis was not available.

Here, we describe the successful development of an orientation procedure with very high resolution independent of magnetic data. Test data were acquired in the 2.5-km-deep ICDP Outokumpu Research Hole in eastern Finland (Kukkonen, 2007) with the so-called Göttinger Borehole Magnetometer (GBM). The sonde uses three fiber optic gyros (FOGs) exhibiting a small drift of $1.5^{\circ}h^{-1}$ and a high resolution of $9x10^{-5}$ degrees. In combination with a built-in Förster magnetometer triplet, the GBM can record the magnetic field in three components as well as the tool orientation continuously. In the Outokumpu drill hole, errors (root mean square) were 0.14° for the inclination and 1.4° for the declination of the magnetic flux density.

Technical Details and Data Preparation

The GBM sonde (3.25 m long, 68 kg) has a diameter of ~86 mm and approximately 140 mm including the centralizer (Fig. 1). The magnetic sensor group of the GBM consists of three Förster magnetometers with a maximum amplitude range of ±50,000 nT for the horizontal components (B_x, B_y) and ±70,000 nT for the vertical component (B_z). The resolution is 6.1 nT for B_x and B_y and 8.5 nT for B_z. The fiber optic gyros have a temperature-dependent drift which is minimal for temperatures above 32°C. Furthermore, the Gaussian noise of the FOG data decreases with increasing temperature to an average of $2x10^{-3}$ degrees in all components. In order to provide optimal operating conditions, the FOGs are mounted in an aluminum cylinder which is thermally isolated against the housing and actively heated by heater elements. To determine the temperature dependent characteristics for posterior recalibration, we conducted several calibration measurements. Due to the delicate electronics inside the FOGs, the maximum ambient operating temperature is 71°C.

High demands on accuracy require extensive data processing. The first step is the calibration of the Förster probe triplet. The calibration measurements have been done in a magnetic laboratory equipped with a Braunbek coil system with active field compensation (Glassmeier et al., 2007). The quasi-zero-field region inside the Braunbek sys-tem has a residual field of <1 nT. With this system it is possible to determine the sensor offsets, the misalignment between the three sensor axes, and the scaling factors between measured data and genuine field. An alternative method is based on measurements in at least twelve positions while the external field has to be constant (Auster et al., 2002). By minimizing the differ-ence between the external and the measured field, the calibration factors can be computed. Another important step is the drift correction of the FOG data,

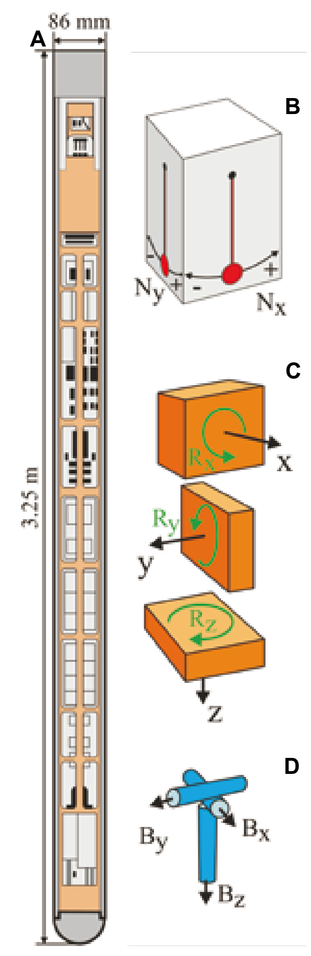

Figure 1. [A] Schematic sketch of the GBM [B] inclinometer, [C] fiber-optic gyros, [D] Förster-magnetometer triplet.

using the temperature-dependent calibration factors previously determined in the laboratory. Finally, the actual reorientation procedure is carried out, which transforms the magnetic data from tool to geographical coordinates using the orientation information provided by the FOGs.

Case Study from the Outokumpu Deep Drillhole

The GBM sonde was utilized in a logging campaign in the Outokumpu research borehole in eastern Finland (Fig. 2) in September 2008. This 2516-m-deep well was drilled from 2004 to 2005 and is maintained by the Geological Survey of Finland as a deep geolaboratory. It offers ideal conditions for magnetic measurements as it cuts through a highly magnetized 200-m-thick Cu-Co-Zn bearing ophiolitic layer (1300–1500 m) at moderate temperatures below 40°C (Kukkonen, 2007).

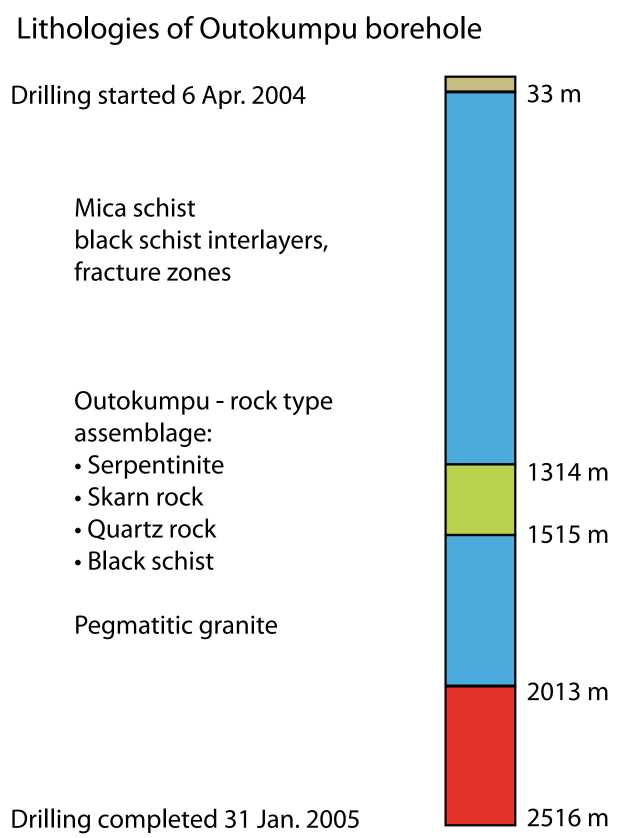

Figure 2. Borehole scheme of the Outokumpu well with simplified lithological units (Kukkonen, 2007).

Figure 3 shows a comparison of downlog and uplog data of sample measurements before and after reorientation. The mean difference between downlog and uplog in the total field (Fig. 3A) is on the order of 30 nT. The horizontal components after recalibration, but before reorientation, are depicted in Figs.3B and 3C. The large variations of ±11,200 nT are due to the rotation around the vertical axis. Depth regions with rapid changes (e.g., at 800 m), which are produced by sudden rotations, can be observed. A possible explanation is that they are caused by borehole wall outbreaks. The cable tension built up by the use of non-rotating centralizers may be released in such breakout sections. This hypothesis is supported by an observed co-occurrence between sections of rapid tool rotation and increasing caliper.

For the reorientation procedure, the magnetic data from the internal tool coordinate system xyz are projected onto the geographical system North, East, and Vertical (downwards). Each magnetic data triplet is multiplied by a rotation matrix computed from the FOG's data. Furthermore, other effects have to be considered, one of which is the Earth's rotation. The fiber optic gyros measure rotation depending on their orientation with respect to Earth's rotational axis, in addition to the tool rotation. Therefore, the Earth's rotational vector has to be projected into the tool system and subtracted from the FOG data in all three components for each depth.

The next processing corrects the misalignment of the FOG system. If the three axes of this system are not exactly perpendicular to each other, rotation around the z-axis will cause a spurious signal in the x- and y-gyros, which would be mistaken for a real rotation. Due to the torque in the cable, the rotation around the z-axis dominates. Thus, we consider only the misalignment between the x- and z-axis, as well as y- and z-axis, which were determined by calibration measurements to be 0.19° and 0.02°, respectively.

Another challenge is the computation of the rotation matrix itself. During the sampling period of 0.5 seconds, rotation occurs continuously around all three axes. However, when computing the rotation matrix, one has to assume rotation in a specific order—for instance, in roll-yaw-pitch convention. Instead of using only one rotation matrix per step, the movement is smoothed by dividing the period into fifty steps. Each matrix corresponds to a rotation by only 1/50 of the measured rotation angles. This reduces the error particularly in regions where fast rotations in all three axes exist.

The final correction takes the tool orientation above ground into account. Before actually starting the logging, the tool is set up in a vertical position above the borehole and is aligned to a north marker by a sighting telescope mounted on the housing. This defines the start orientation in the FOG data with an accuracy of $5x10^{-2}$ degrees. Having finished the uplog this procedure is repeated, so that the orientation at these two time points can be ensured. If the reorientation procedure works perfectly, the two orientations should match exactly after processing. Nevertheless, differences of a few degrees are usually observed in all three components. Based on these deviations, additional drift corrections are computed and applied to the FOG data to minimize the orientation differences. In Figs. 3D–3F, the example logs are shown after the complete reorientation procedure.

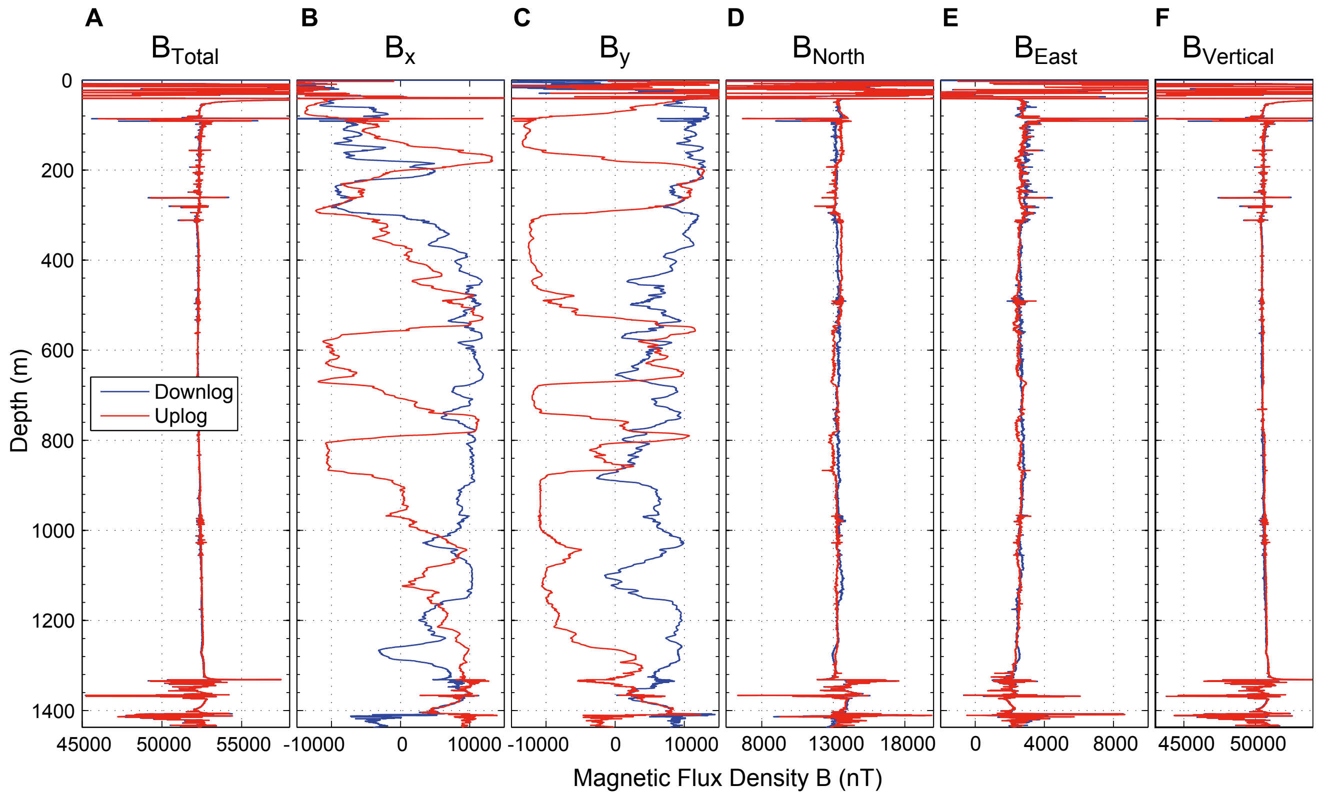

Figure 3. [A] Total magnetic flux density, [B and C] horizontal components before reorientation (internal tool coordinates xyz), [D–F] magnetic flux density after reorientation with geographic coordinates North, East, Vertical.

Quality Assessment

One possibility to assess the quality of the reorientation procedure is the comparison between the uplog and the downlog. For a quantitative evaluation, we use the root mean square (RMS) of the difference. This results in errors of RMS_{Total} = 50 nT, RMS_{North} = 250 nT, RMS_{East} = 180 nT, and $RMS_{Vertical}$ = 75 nT for the total, north, east, and vertical components, respectively. The deviations are not equally distributed. In regions between two fast rotations (e.g., 800–880 m), the discrepancy reaches up to 500 nT. There are also sections where the deviation is much smaller (less than 45 nT) in all three components between 680 m and 750 m. The errors of inclination and declination of the magnetic flux density result are $RMS_{Inclination} = 0.25^{\circ}$ and $RMS_{Declination} = 0.75^{\circ}$, respectively.

Besides comparing downlog and uplog in the same measurement, the reproducibility between different logs is also an important criterion. In Fig. 4, two logs measured on

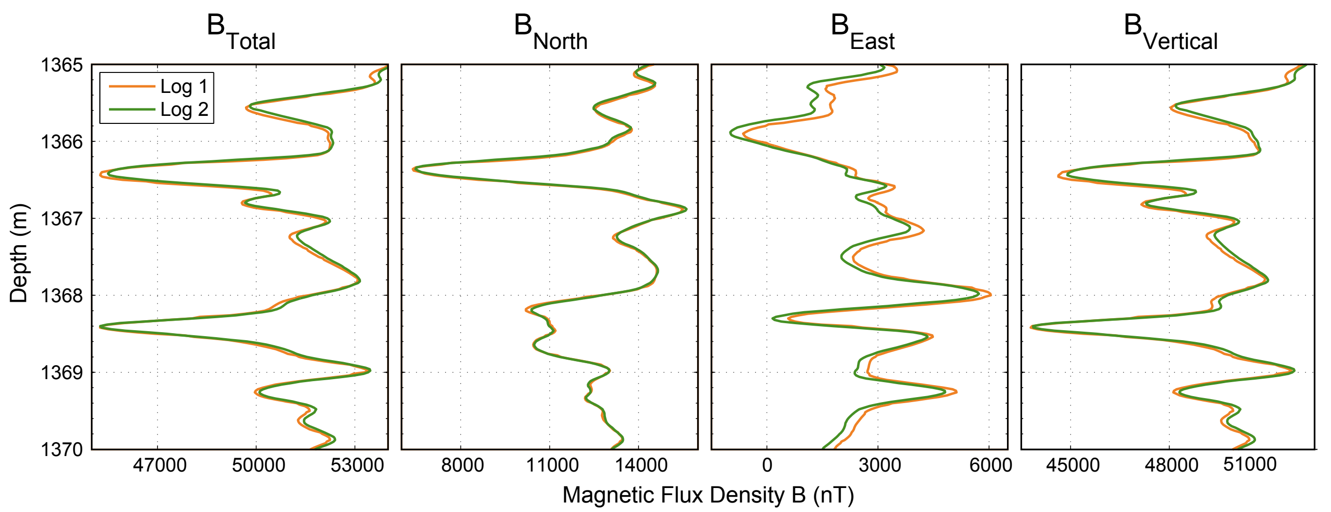

Figure 4. Comparison between two different logs, extract of strongly magnetized region. Each line represents the mean value of downlog and uplog.

two consecutive days under identical conditions are shown. Each log consists of the average value of the corresponding downlog and uplog. To illustrate the spatial resolution, a section of the strongly magnetized Outokumpu rock assemblage is shown in detail (Fig. 4). All features are reproduced very well. The average amplitude deviations between the two logs are 170 nT in the total and vertical components, 10 nT in the east component, and 330 nT in the north component. The deviations in orientation are $RMS_{Inclination}$ = 0.14° and $RMS_{Declination}$ = 1.4°.

Outlook

The logging results from the Outokumpu drill hole are used to calculate the rock magnetization, based on a model developed by Bosum et al. (1988). Existing susceptibility measurements are used to separate remanent from induced magnetization. Preliminary results indicate that the direction of remanent magnetization is inhomogeneous and scattered. From a statistical analysis we were able to identify two preferred directions of remanent magnetization which might be related to the genesis of the Outokumpu rock assemblage in the depth region of 1300–1440 m. The results of the ongoing detailed analysis including magnetic laboratory measurements will be reported elsewhere. Based on the comparison of our *in situ* direction of remanent magnetization with direction measured in the laboratory, we might also be able to carry out a reorientation of core samples from this section.

We will continue to improve the accuracy of the reorientation procedure. Presently, the main source of error is the fast rotation of up to 10° around the z-axis during the sample period of 0.5 seconds. Since the sampling period is limited by the data transfer rate to the base station, an upgrade of the tool hardware is desirable. We plan to implement a flash memory, which will enable us to increase the sampling frequency by twenty-fold. This will also enhance the spatial resolution of the tool using the same logging speed. Furthermore, we intend to carry out extended calibration measurements to obtain the misalignment angles between all three FOG axes and their scaling factors. We will also re-measure the calibration factors of the magnetic sensors, considering possible temperature dependence. We aim for errors less than 0.1° for both inclination and declination of the magnetic flux density.

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Related Web Link

http://www.gsf.fi/projects/o_k_deepdrilling/

Seismic Prediction While Drilling (SPWD): Looking Ahead of the Drill Bit by Application of Phased Array Technology

by Katrin Jaksch, Rüdiger Giese, Matthias Kopf, Andreas Jurczyk, Stefan Mikulla, Stefan Weisheit, Marco Groh, and Kay Krüger

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Introduction

Geophysical exploration is indispensable for planning deep drilling. Usually 2D- or 3D-seismics investigations are applied and, depending on the resulting geologic model for the underground, the drill site and drilling path are determined. In recent years the focus of exploration has shifted towards small-scale geological structures such as local layers and faults. Depending on the source frequencies and the target depth, 2D- or 3D-seismics from surface cannot always resolve such structures in particular at larger depths. In general, signal frequencies of about 30–70 Hz are typical for surface seismic methods. The deeper and smaller the sought-after structures are, the worse will be the resolution. Therefore, borehole seismic measurements like Vertical Seismic Profile (VSP) or Seismic While Drilling (SWD) have been developed (Fig. 1). For the VSP method geophones are normally integrated in the borehole, while the seismic source generates seismic waves at the surface. The SWD method uses the drill bit as the seismic source. Hence, the quality of the seismic signals is highly dependent on the drilled rock and the type of drill bit, but even well-suited rock conditions and adequate drilling may not provide sufficient data quality.

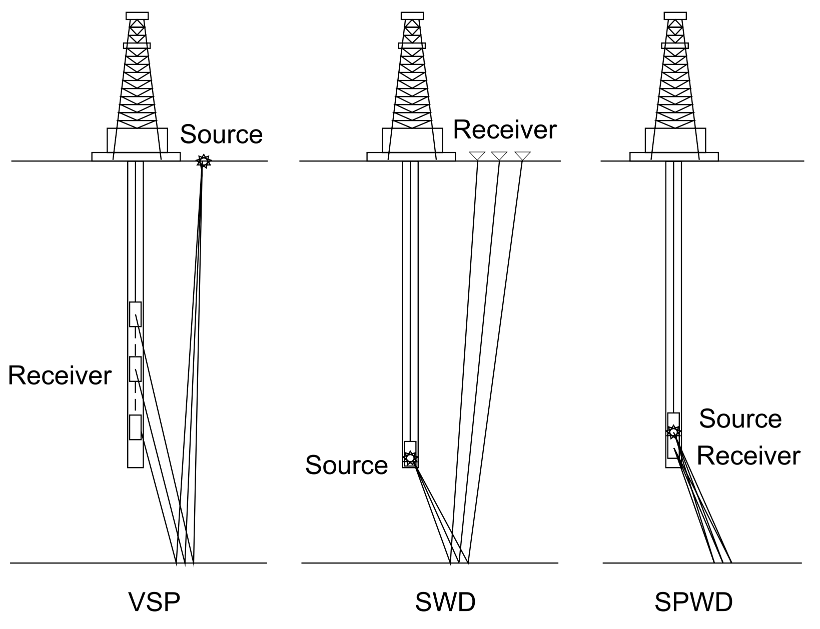

Figure 1. Comparison of the different seismic borehole exploration methods VSP, SWD, and SPWD

Compared to 2D- and 3D-seismics, the distances between source and receiver to the target are shorter for VSP, and for SWD in particular. Signal frequencies up to about 100 Hz are observed yielding a slightly better resolution compared to surface seismics. However, subtle yet important features (e.g., fault zone) often cannot be identified with certainty. Accordingly, a method or tool that would improve the resolution is of high importance since this would allow adjusting the drilling path to minimize risks and costs of drilling.

A device combining source and receiver immediately behind the drill bit would allow seismic exploration of a range of about 50–100 m ahead of the drill bit with a resolution of one meter. The first prototype of such a Seismic Prediction While Drilling (SPWD) device has been designed and manufactured within this project (Wenke et al., 2010). The tool uses signal frequencies between 500 Hz and 5000 Hz, which are significantly higher than the usual VSP and SWD applications.

A Laboratory Prototype for Seismic Prediction in Boreholes

A SPWD prototype was designed for laboratory conditions without the impact of borehole fluids, high temperatures, and pressures and only for tests in horizontal boreholes. It consists of different units for seismic sources, receivers, and data logger. Figure 2 and Table 1 provide details of the instrumentation and dimensions. Four standard magnetostrictive actuators (AK1 to AK4; Fig. 2) are aligned along the borehole axis to serve as a cascading source and act as seismic sources. Every single actuator unit can be rotated in steps of 15° around the longitudinal axis of the prototype to allow for a variety of source configurations trials.

Table 1. Parameters of the prototype

Length	1.81 m
Diameter	20–23.5 cm
Weight	~60 kg
Pressing	pneumatic, 6–8 bar
Contact pressure:	
actuators	~ 2 kN
geophones	~ 200 N

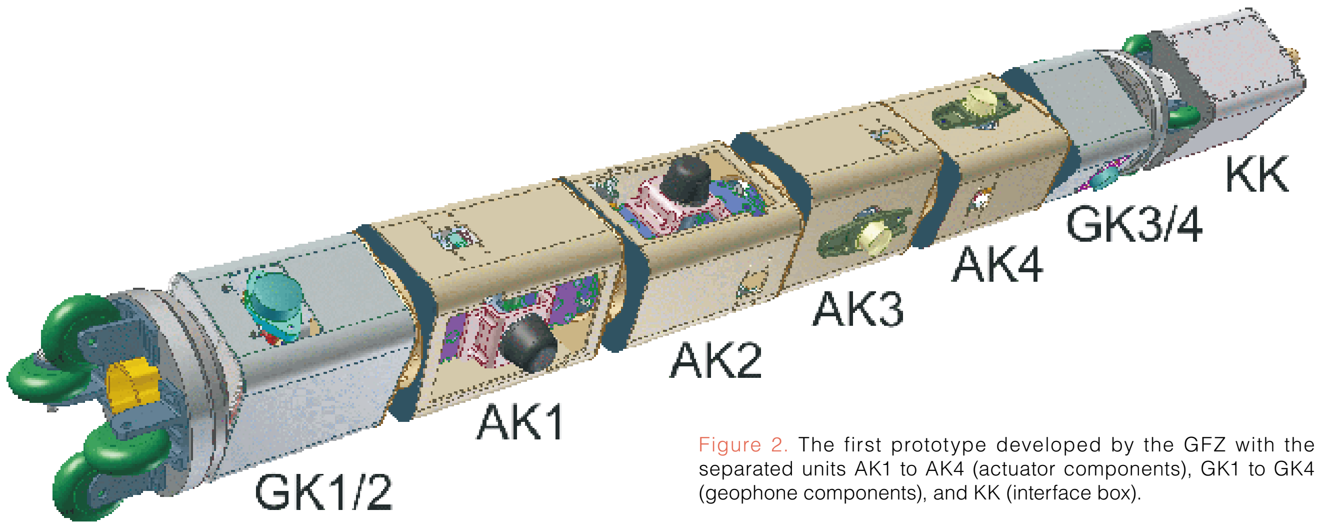

Figure 2. The first prototype developed by the GFZ with the separated units AK1 to AK4 (actuator components), GK1 to GK4 (geophone components), and KK (interface box).

The receivers used are four 3-component geophones integrated in two geophone units (GK1/2 and GK3/4; Fig. 2) with each 3-component geophone mounted in opposite alignment. Again, the geophone units can be rotated in 15° increments perpendicular to the borehole axis. This allows receiving the seismic response from the surrounding rock in defined space directions adjusted to the actuator positions.

The data logger unit (KK; Fig. 2) includes the interface with the external feed cables and the data logger which is used for source activation, triggering, and seismic data acquisition. Additionally, a sensor for inclination, a compass, and an odometer are integrated to determine the position and orientation of the SPWD device in the borehole. An infrared camera at the top monitors the borehole wall.

Several guide rollers are mounted at the top and the end to move the prototype slightly in the borehole. In order to take measurements, the actuators and geophones must be pressured radially to the borehole wall. The prototype is automatically centered in the borehole. The actuators are decoupled from the prototype body so that all seismic energy is initiated exclusively in the borehole wall.

The actuators are controlled in amplitude and phase. Acceleration sensors are integrated in the front stamps of the actuators to measure the emitted seismic signals. With respect to a specific radiation pattern, the signal for each actuator is calculated based on the local coupling conditions at the borehole wall and then applied.

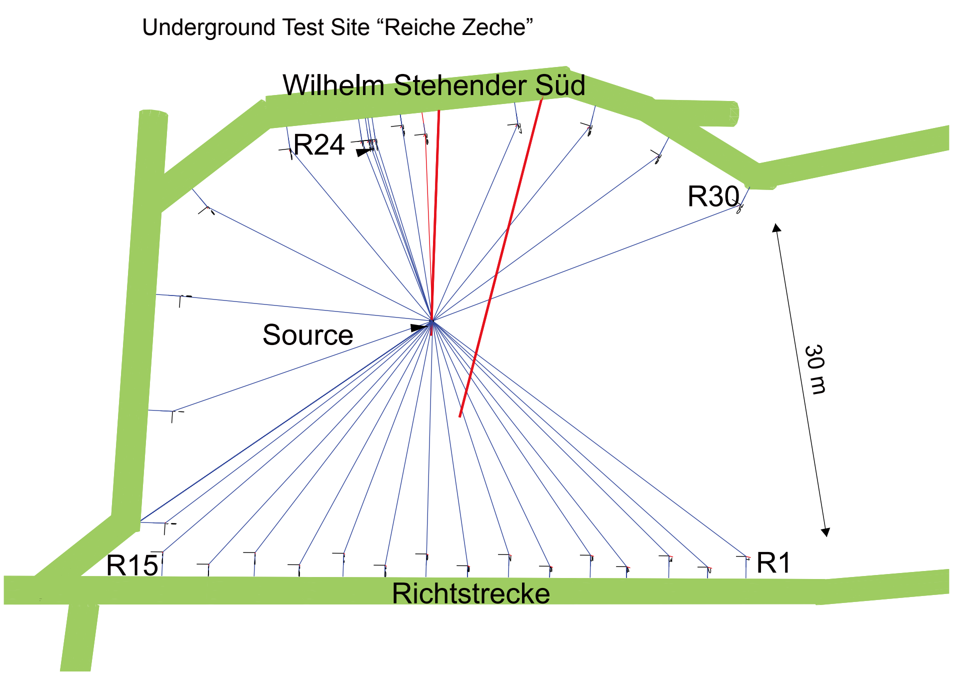

Figure 3. The test site of the GFZ at the education and research mine "Reiche Zeche" in plain view with the three surrounding galleries (green), the boreholes (red), and the geophone anchors (R1-R30, black). The lower horizontal gallery is named Richtstrecke; the upper gallery is called Wilhelm Stehender Süd.

Test Environment

A test site in the education and research mine "Reiche Zeche" in Freiberg, Germany (Wenke et al., 2010) has been constructed to ensure constant environmental conditions. Surrounded by three galleries, the site comprises a block of homogeneous high-grade gneisses of almost 50 m x 200 m. Previously used as a test site for seismic sources and receivers of an integrated seismic imaging system (Giese et al., 2006), the site has been expanded. Over thirty 3-component geophone anchors one or two meters long are installed around the area about 4–9 m apart (Fig. 3).

Two horizontal boreholes of 20 m and 30 m length were drilled towards a gallery to test the prototype. Diamond coring was applied to yield both high-quality cores and true-to-size caliber. The latter was only disrupted at two centimeter-sized fracture zones which appear to pass through the whole rock block and which are filled with quartz, feldspar, clay, and fluids. The dike-like fault zones and the galleries act as well-defined reflectors for the borehole seismic measurements.

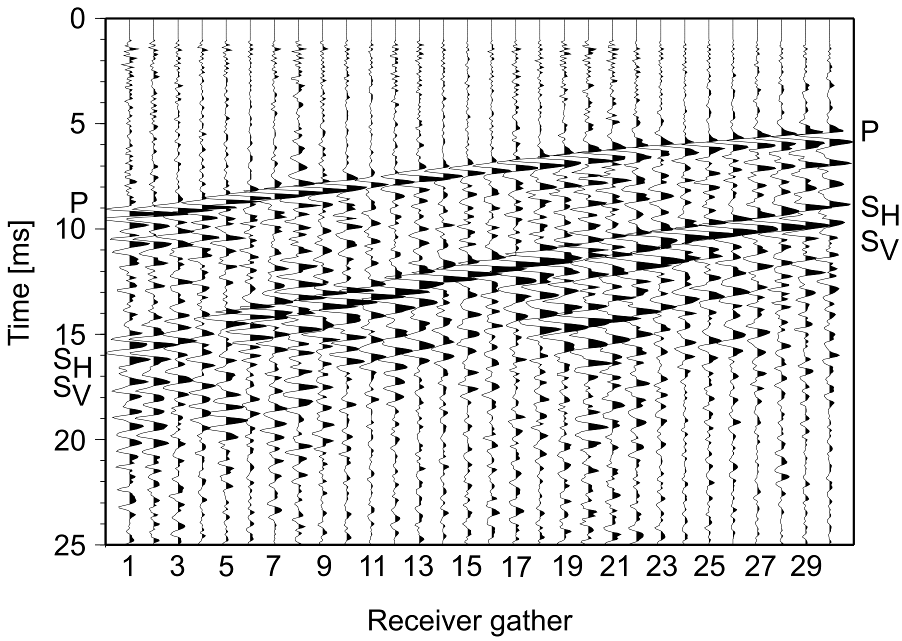

Figure 4. Seismic data of the vertical component at receiver 16 with 30 equidistant shot points in the 30 m borehole. The seismic wave field shows distinct compression (P) and shear (SH, SV) waves and overall a good signal-to-noise ratio.

Seismic Measurements

Several measurements were implemented during the first year to test the functionality of the different units of the prototype (e.g., the pneumatic contact pressure and the handling of the prototype with rods in the borehole). The performance of the actuators was examined to adapt the parameters of the sweep signals and to maximize the energy of the seismic source in order to reach a sufficient exploration range.

To achieve a directional radiation effect it is essential that all four actuators can be controlled independently of each other. An increased radiation of seismic wave energy in the direction of the borehole axis allows the view in areas to be drilled. Therefore, every actuator related to amplitude and phase of the source signal must be controlled. The next step for focusing the seismic waves is to use the method of phased array, which has been developed in material sciences and for medical diagnostics by sonography (Hedrick and Hykes, 1996). The signal phases for each actuator can be determined depending on the seismic wave velocities of the surrounding rock, the distance of the actuators to each other, and the frequencies used. Furthermore, the influence of the seismic velocity on the radiation pattern was studied by applying a sonic log with the actuators with a broad frequency band (1–14 kHz).

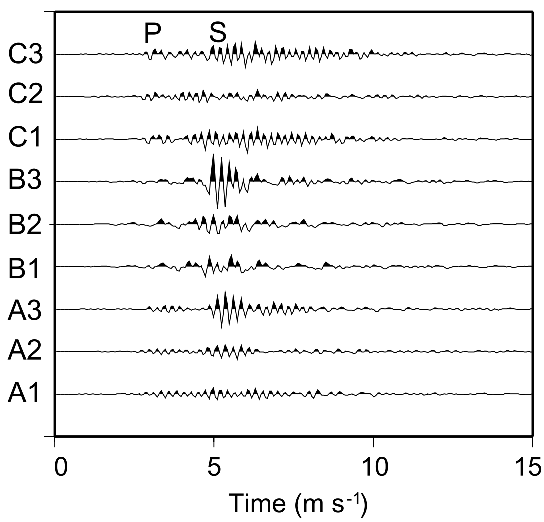

Figure 5. Correlated 3-component recordings of the direct compressional (P) and shear (S) waves at receiver 24 (see R24 in Fig. 3). The source-receiver offset is 17 meters. A – vertical component traces, B – horizontal component traces, C – radial component traces; 1 – sources are in phase, 2 – seismic wave field directed towards Richtstrecke, 3 – seismic wave field directed towards Wilhelm Stehender Süd.

The influence of different seismic source arrangements was investigated in order to achieve the directional characteristics. The main goal of the measurements was to focus the initiated seismic waves in the direction of the borehole axis.

Results

The borehole data overall show a good signal-to-noise ratio. The direct seismic wave field indicates distinct compression and shear waves (Fig. 4). As expected, the anisotropic gneisses cause shear wave splitting of about ten percent. The quality of the seismic data in amplitude and frequency spectra correlates strongly with the fracture density of the rock along the borehole, which was determined with an optical borehole scan and on core. These regions are associated with a lower signal-to-noise ratio. Independent of the local rock conditions, the borehole data show seismic reflections from ahead and rearwards. In particular the reflections from the gallery ahead are used for the calibration of focusing.

Analysis of several seismic measurements with a focus on the direct seismic waves shows that the phased array technology influences explicitly the directional characteristics of the radiated seismic waves. Their amplitudes can be enhanced three times more in the desired direction and can simultaneously be attenuated in the reverse direction. Figure 4 and 5 present a set of exemplary data recorded at the receiver in geophone anchor R24 (Fig. 3). The source is positioned close to the bottom of the borehole. The frequency content of the source signal is between 500 Hz and 5000 Hz. P-waves arrive at about 3 ms and S-waves at 4.8 ms, corresponding to seismic wave velocities of 5700 m s^{-1} and 3500 m s^{-1}, respectively. The amplitudes of the P-wave are highest on the radial component (C in Figs. 4 and 5) directed to the source. The amplitudes of the S-wave are highest perpendic-ular to the P-wave on the vertical (A) and horizontal component (B). If the source wave field is directed towards the gallerie "Wilhelm Stehender Süd" (Fig. 3), the amplitude of the S-wave is clearly amplified (B3 and C3) in comparison to source signals without manipulation of wave field direction (B1 and C1). A slight increase of P-wave amplitudes can also be observed in the radial component in C3 compared to C1. If the wave field is directed towards the gallery "Richtstrecke" (Fig. 3), the amplitude decreases slightly on the radial component C2 compared to original source wave field in C1, whereas no significant reduction of amplitudes is observed on the vertical (A2) and horizontal (B2) components.

Conclusions

The application of the phased array technology for the directional investigation of borehole surroundings is very promising. However, focusing of the seismic waves has to be improved to maximize the energy in the desired direction. For that purpose several measurements and modeling of different source and receiver configurations must be done to calibrate the initiated seismic signals of the sources. The application of a phased array source system influences the processing and imaging of the data. Methods developed for surface seismic and VSP measurements have to be adapted to take advantage of the improved data quality and known directional information of the recorded wave field.

The next step will be the development of a wireline SPWD prototype for vertical boreholes with depths to 2000 m. Modifications in the arrangement of the different units will be necessary, as well as an adaptation to fluid-fill under the conditions in deep boreholes with respect to pressure and temperature. If the wireline prototype tests successfully, we plan to implement the tool into the downhole assembly of a drill string as a Logging-While-Drilling tool. This would allow a seismic prediction of structures or faults while drilling and will help to reduce risks encountered while drilling.

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Arctic Ocean Scientific Drilling: The Next Frontier

by Bernard Coakley and Ruediger Stein

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Introduction

The modern Arctic Ocean appears to be changing faster than any other region on Earth. To understand the potential extent of high latitude climate change, it is necessary to sample the history stored in the sediments filling the basins and covering the ridges of the Arctic Ocean. These sediments have been imaged with seismic reflection data, but except for the superficial record, which has been piston cored, they have been sampled only on the Lomonosov Ridge in 2004 during the Arctic Coring Expedition (ACEX-IODP Leg 302; Backman et al., 2006) and in 1993 in the ice-free waters in the Fram Strait/Yermak Plateau area (ODP Leg 151; Thiede et al., 1996).

Although major progress in Arctic Ocean research has been made during the last few decades, the short- and long-term paleoceanographic and paleoclimatic history as well as its plate-tectonic evolution are poorly known compared to the other oceans. Despite the importance of the Arctic in the climate system, the database we have from this area is still very weak. Large segments of geologic time have not been sampled in sedimentary sections. The question of regional variations cannot be addressed.

Prior to 2004, the geological sampling in the Arctic Ocean was restricted to obtaining near-surface sediments, i.e., only the upper about 5–15 m could be sampled by means of gravity and piston coring. Thus, more or less, all studies were restricted to the Quaternary, with one exception (Fig. 1; e.g., Clark et al., 1980, 1986; Thiede et al., 1990). In four short sediment cores from Alpha Ridge, upper Cretaceous and lower Tertiary sediments were sampled by gravity coring from ice island T-3. Until recently (Stein, 2008), the absence of technological and logistic solutions for reaching and operating in a permanently ice-covered region thwarted further study of the Arctic Ocean; thus, we have been unable to retrieve long and undisturbed sediment cores.

With the successful completion of IODP Expedition 302 ("Arctic Coring Expedition", ACEX)—the first Mission Specific Platform (MSP) expedition within the Integrated Ocean Drilling Program (IODP)—a new era in Arctic research has begun. For the first time, scientific drilling in the permanently ice-covered Arctic Ocean was carried out, penetrating about 430 m of Quaternary, Neogene, Paleogene, and Campanian sediments on the crest of Lomonosov Ridge close to the North Pole (Backman et al., 2006, 2008; Moran et al., 2006).

ACEX was an outstanding success for two reasons. First, ACEX has proven that with an intensive ice-management strategy (i.e., a three-ship approach with two icebreakers *Sovetskiy Soyuz* and *Oden* protecting the drillship *Vidar Viking* by breaking upstream ice floes into small pieces), successful scientific drilling in the permanently ice-covered central Arctic Ocean is possible. Second, the first scientific results brought new and unexpected insights into the Arctic Ocean climate history and its global significance (Backman and Moran, 2008, and further references therein).

Despite the success of IODP Expedition 302, major questions related to the climate history of the Arctic Ocean and its long- and short-term variability during Mesozoic-Cenozoic times cannot be answered from the ACEX record due to the poor core recovery and, especially, a major mid-Cenozoic hiatus. This hiatus spans the critical time of the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world (Miller et al., 1987, 1991; Lear et al., 2000; Pearson and Palmer, 2000; Zachos et al., 2001). Nevertheless, the success of ACEX has certainly opened the door for further scientific drilling in the Arctic Ocean. The ACEX results will frame the next round of questions to be answered from new drill holes to be taken by a series of drilling legs during the next decades.

Workshop on "Arctic Ocean History: From Speculation to Reality"

In order to discuss and plan the future of scientific drilling in the Arctic Ocean, an international workshop was held at the Alfred Wegener Institute in Bremerhaven, Germany, on 3–5 November 2008 (Coakley and Stein, 2008). The coauthors of this article convened that workshop. About ninety-five scientists from Europe, the U.S.A., Canada, Russia, Japan, and Korea as well as observers from oil companies participated in the workshop. All participants were invited to submit abstracts about their experiences, ideas and/or plans of Arctic Ocean research with special emphasis on drilling.

The major targets of the workshop were as follows: (1) to bring together an international group of Arctic scientists, young scientists, and ocean drilling scientists to learn and exchange ideas, experience, and enthusiasm about the Arctic Ocean; (2) to develop a scientific drilling strategy to investigate the tectonic and paleoceanographic history of the Arctic Ocean and its role in influencing the global climate system; (3) to summarize the technical needs, opportunities, and limitations of drilling in the Arctic; and (4) to define scientific and drilling targets for specific IODP-type campaigns in Arctic Ocean key areas to be finalized in the development of drilling proposals.

The first day of the workshop focused on presentations about the history of the Arctic Ocean, the legacy of high latitude ocean drilling, the existing site survey database, the possibilities of collaboration with industry, and the process of developing ocean-drilling legs through IODP. The next day and a half was spent in thematic and regional break-out groups discussing the particular questions to be addressed by drilling and the particular targets for Arctic scientific drilling. Within the working groups, key scientific questions, site surveys (available and needed), and strategies for reaching the overall goals were discussed, and—as one of the main results—core groups for further developing drilling proposals were formed.

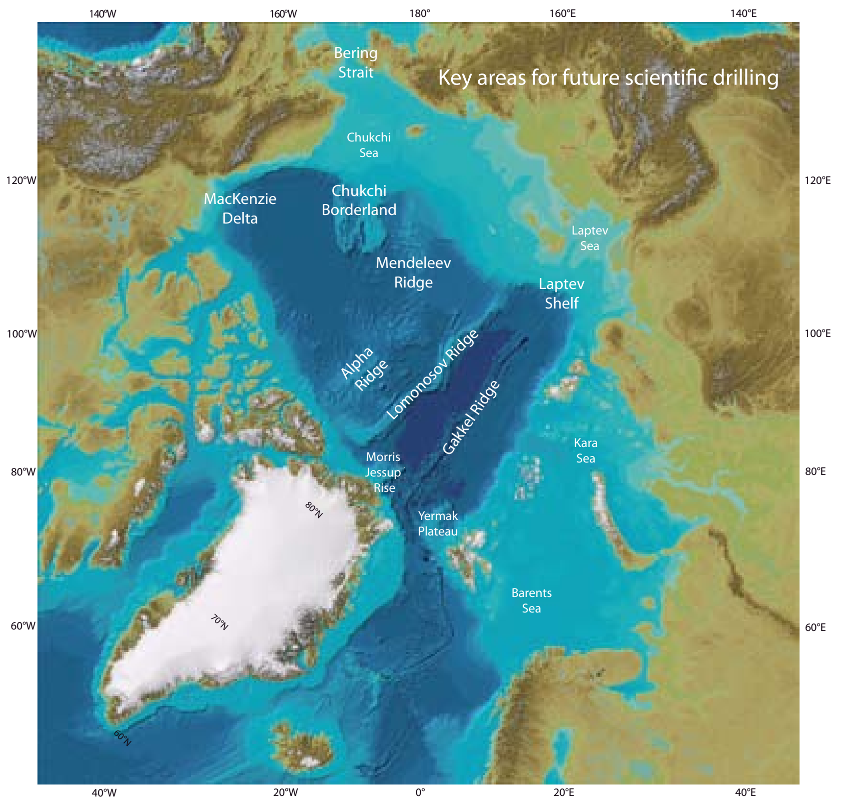

Figure 1. The proposed drilling regions for the Arctic are primarily ridge tops, which will have condensed sections, making it possible to sample relatively long intervals without deep penetration of the seabed. There is also a desire for expanded, high resolution, sections, which can be recovered from the continental shelves. (Background map is from IBCAO, Jakobsson et al., 2008)

Based on discussions at this meeting, a number of new proposals will be submitted to IODP in 2009/2010, a critical time both for the future of Arctic Ocean science and the future of scientific ocean drilling. As of October 2009, eight active Arctic-related proposals are listed in the IODP system (Table 1). Major themes (hypotheses to be tested by drilling) identified by the workshop participants may be summarized as follows:

Paleoceanography:

- Cyclicity between oxic, sub-oxic, and/or euxinic/anxoic conditions during the Cretaceous and Paleocene-Eocene
- Greenhouse vs. icehouse climate
- Polar amplification of greenhouse warming
- Hydrological cycle during greenhouse warming
- Onset of Eocene cooling
- Impact of Eocene-Oligocene transition in global pCO_2 and sea level on the Arctic
- Onset and variability of sea-ice cover (seasonal vs. perennial ice cover)
- Circum-Arctic ice-sheet/ice-shelf history and dynamics
- Opening of Bering Strait/Fram Strait and its paleoceanographic consequences
- Causes of extended mid-Cenozoic unconformities
- Nature of the Arctic environment during periods of extreme events (warm/cold)
- Bipolar synchronous vs. asynchronous climate variability?

The varied sedimentary environments of the Arctic Ocean (Stein, 2008) enable two types of studies. Sampling on the tops of the ridges that segment the basin make it possible to collect records that span long intervals of geologic time. Focusing on the shelves and near-shelf areas make it possible to collect expanded, high-resolution records suitable for detailed paleo studies. At the workshop there was little interest in drilling into basinal sediments, given the expectation that these records are largely composed of turbidites and other mass-wasted sediments.

In order to study the long-term Mesozoic-Cenozoic evolution of the Arctic Ocean, we need to obtain undisturbed and complete sedimentary sequences to be drilled along depth transects across the major ocean ridge systems, i.e., the Lomonosov Ridge, the Alpha-Mendeleev Ridge, and the Chukchi Plateau/Northwind Ridge (Fig. 1). High-resolution records will enable detailed studies of climate variability on Milankovich and millennial to sub-millennial time scales. Appropriate sediments can be drilled along the circum-Arctic continental margins characterized by high sedimentation rates. Key areas, for example, are the Kara and Laptev seas and the Mackenzie shelf/slope characterized by large river discharge (Fig. 1). Key locations for studying the history of exchange of the Arctic Ocean with the world's oceans are the Fram Strait/Yermak Plateau and Chukchi Plateau areas (Fig. 1).

Tectonics:

- Mode of crustal extension in the Laptev Sea shelf
- Development of the Fram Strait gateway (mode of extension)
- Identification of plate boundaries (Chukchi Plateau)
- Age of magnetic anomalies (Canada Basin)
- Age and evolution of Alpha Ridge, Mendeleev Ridge, Makarov Basin, and Chukchi Plateau
- Correlation of onshore and offshore geology (Paleozoic sediments, Mesozoic magmatism)
- Understanding the 'Amerasia' side of Lomonosov Ridge
- Along-strike geologic variation of Lomonosov Ridge and consequences for Mesozoic evolution

Petrology:

- Gakkel Ridge (Fig. 1) mantle melting and geochemistry: western vs. eastern Gakkel Ridge (Global problem: how does continental lithospheric mantle contribute to melting of the asthenosphere? How does extent of melting change as spreading rate goes to zero?)
- Nature and origin of the Chukchi Borderland volcanism
- Origin of Alpha Mendeleev Ridge (hotspot track or segment of a large LIP?) Is the roughly synchronous volcanism recognized in America and Asia somehow related to a High Arctic Large Igneous Province?

Gas Hydrates:

The stability of gas hydrates and permafrost below the seafloor are intimately related to climate change (greenhouse gas reservoir). The dissociation of hydrates, which some believe is now underway, could release large quantities of methane to the atmosphere, acting as positive feedback driving global warming and further destabilizing sub-sea permafrost. These processes can destabilize the seafloor, enabling slope failures and thermo-karst as well as influencing biogeochemical processes. Gas hydrates may also be useful energy resources.

A pan-Arctic objective for scientific drilling would be to sample multiple locations that represent different aspects of gas hydrate (GH) evolution and its relationship to climate and geologic history of the Arctic. These could include the MacKenzie shelf (most mature, representative of a deltaic end-member; Fig. 1), the Russian shelf (Laptev Sea, excellent location, wide shelf, but not as mature; Siberia excellent candidate for GH aspect; Fig 1), deep-water locations, particularly Mendeleev Ridge, where pockmarks and other seismic evidence support the presence and venting of sub-seafloor gases. Integrating the role of GH from these areas will be necessary to understand larger scale phenomena (e.g., carbon cycle).

Site Surveys

For the precise planning of future drilling campaigns (including site selection, evaluation of proposed drill sites for safety and environmental protection aspects, etc.), compre-

Table 1. Active Arctic-related IODP proposals (as of October, 2009). More details on these proposals including the list of co-proponents and involved institutions can be obtained from the IODP website (http://www.iodp.org/active-proposals).

Number	Short Title	Contract Proponents	University/ Institute	Country	Platform*	E-mail
645-Full3	North Atlantic Gateway	W. Jokat	AWI Bremerhaven	ECORD/ Germany	MSP+NR	Wilfried.Jokat@awi.de
680-Full	Bering Strait Climate Change	S. J. Fowell	University of Alaska Fairbanks	USA	MSP	ffsjf@uaf.edu
708-Pre	Central Arctic Paleoceanography	R. Stein	AWI Bremerhaven	ECORD/ Germany	MSP	Ruediger.Stein@awi.de
746-Pre	Arctic Mesozoic Climate	W. Jokat	AWI Bremerhaven	ECORD/ Germany	MSP	Wilfried.Jokat@awi.de
750-Pre	Beringia Sea Level History	L. Polyak	Ohio State University	USA	MSP+NR	Polyak.1@osu.edu
753-Pre	Beaufort Sea Paleoceanography	M. O'Regan	Stockholm University	ECORD/ Sweden	NR	Matt.oregan@geo.su.se
755-Pre	Arctic Slope Stability	D. Winkelmann	GEOMAR	ECORD/ Germany		dwinkelmann@ifm-geomar.de
756-Pre	Morris Jesup Rise: Drilling the Arctic Ocean Exit Gateway	M. Jakobsson	Stockholm University	ECORD/ Sweden		Martin.jakobsson@geo.su.se
*NR = Non-Riser MSP = Mission Specific Platform						

hensive site survey data are needed. The lack of good site survey data and age control for existing seismic reflection records is one of the biggest limitations on the development of Arctic Ocean scientific drilling (see the JEODI Report of Kristoffersen and Mikkelsen, 2004).

For some of the potential study areas, the site survey data base is already quite good. For example, from the Lomonosov Ridge, a large number of deep penetration reflection seismic profiles were acquired on icebreaker-based expeditions in 1991, 1996, 1998, and 2005 (Fütterer, 1992; Kristoffersen et al., 1997; Darby et al., 2005; Jokat, 2005 and further references therein). An intensive PARASOUND survey (in combination with coring) was carried out in 1995 and 1998 (Rachor, 1997; Jokat et al., 1999), and the first high-resolution chirp profiles were collected in 1996 (Jakobsson, 1999). In 1999, the SCICEX program collected high-resolution chirp sub-bottom profiler data, swath bathymetry and side-scan sonar backscatter data on Lomonosov Ridge from an American nuclear submarine (Edwards and Coakley, 2003), contributing significantly to the much improved bathymetric chart of the Arctic Ocean (Jakobsson, 2002; Jakobsson et al., 2008). During the 1995, 1996, and 1998 expeditions, a large number of sediment cores were taken by piston, gravity, and Kastenlot corers in the Lomonosov Ridge area (Backman et al., 1997; Rachor, 1997; Jokat et al., 1999; Stein et al., 2001). That means, in combination with the results from the ACEX drilling campaign (Backman et al., 2006, 2008), future drill areas/sites on Lomonosov Ridge can be identified more accurately. On the other hand, in other key areas for future drilling (e.g., the Alpha-Mendeleev Ridge), site survey expeditions still have to be carried out before a detailed planning and drill site selection can start.

Outlook

While sampling in the Arctic Ocean is called out as a priority in many of the sections of the IODP Science Plan, these priorities have yet to be realized in a sampling program of commensurate scope and urgency. Concerning the short- and long-term evolution of the Arctic Ocean and its importance for the understanding of the global climate history, most of the key questions mentioned above, as well as the key areas for scientific drilling in the Arctic Ocean, were already identified on several workshops during the last two decades and published in upcoming reports. Several, especially Thiede and the NAD Science Committee (1992), NAD (1997), Hovland (2001), Bowden et al. (2007), and Coakley and Stein (2009), have to be mentioned here. Over the years, however, scientific drilling in the ice-covered Arctic Ocean remained a dream. The ACEX drilling in 2004 (Backman, et al., 2006) was the first major step to transform this dream into reality. Now, further drilling campaigns are needed to follow up in the future. The construction of a new large icebreaker with deep-water drilling capability will certainly be the next milestone in Arctic Ocean research. Such a vessel would guarantee a commitment to Arctic deep drilling, and in combination with a continuous drilling program, could be a potential contribution to the IODP and succeeding programs, as already outlined in the APPG Report (Hovland, 2001). Plans for the development of *Aurora Borealis*, an icebreaker with deep-water drilling capability (Thiede and Egerton, 2004), are pushed forward over the last few years, and it seems possible that it will be completed and available for the international research community within the next decade. Operation of the *Aurora Borealis* would open a new dimension in multidisciplinary Arctic Ocean research.

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Related Web Link

http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html

IODP Drilling of the "Shackleton Sites" on the Iberian Margin: A Plio-Pleistocene Marine Reference Section of Millennial-Scale Climate Change

by Fatima Abrantes, David Hodell, Gabriella Carrara, Luis Batista, and Henrique Duarte

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Few marine sediment cores have played such a pivotal role in paleoclimate research as those recovered from the Portuguese Margin, including MD95-2039 to MD95-2042 (hereafter referred to as the "Shackleton sites") (Fig. 1). These cores preserve a high-fidelity record of millennial-scale climate variability for the last several glacial cycles and can be readily correlated to Greenland ice cores. Moreover, the narrow continental shelf and proximity of the Tagus River results in rapid delivery of terrestrial material to the deep-sea environment, thereby permitting correlation of marine and ice-core records to European terrestrial sequences. Few places exist in the world's ocean where such marine-ice-terrestrial linkages are possible. Consequently, the Iberian Margin cores have become de facto reference sections for the study of abrupt climate change.

The seminal importance of these sections warrants investment by IODP to ensure that the entire Plio-Pleistocene record is continuously cored and properly recovered with multiple holes at several locations. To this end, we held a drilling workshop ("IODP Drilling of the 'Shackleton sites' on the Iberian Margin: In Search of a Plio-Pleistocene Marine Reference Section") in Lisbon on 9–10 November 2009, sponsored by the European Science Foundation Workshops on Marine Research Drilling - MAGELLAN WORKSHOP SERIES, to formulate a drilling proposal to extend these remarkable sediment archives by drilling with the *R/V JOIDES Resolution* (*JR*). The objectives of the workshop were to assemble researchers who have worked on the Portuguese Margin, especially on the Shackleton sites, to provide a forum for invitees to summarize past work, to present new ideas and data, to identify unanswered key questions, and to discuss the best drilling strategy for reaching the overall goals.

We originally envisioned that the workshop would focus solely on paleoceanography, but during its organization Portuguese and Italian colleagues of the tectonics community approached us. Their interest is to establish a borehole observatory (i.e., CORKed and instrumented hole) in the region of the fault, which is believed to have caused the devastating 1755 Lisbon earthquake and tsunami. Given the societal relevance and importance of these geohazards, we invited seven scientists with tectonic interests to attend the workshop and provide input for potential collaborative drilling to achieve both paleoceanographic and tectonic objectives.

Key paleoceanographic questions that emerged from the workshop including the following. (1) Was the bipolar seesaw a persistent feature of Earth's climate system, or did interhemispheric coupling differ for previous glacial periods? (2) How did millennial-scale variability "evolve" as glacial and orbital boundary conditions changed during the Pleistocene? (3) Did millennial-scale climate variability change in frequency or amplitude across the mid-Pleistocene transition (~920 ka and 640 ka), when the average climate state evolved toward generally colder conditions with larger ice sheets, and the spectral character of climate variability shifted from dominantly 41 kyr to 100 kyr? (4) How do millennial and orbital bands of climate variability interact? (5) What role do millennial-scale events play in triggering glacial terminations? Only by integrating marine and ice-core stratigraphies can we begin to address mechanisms of the coupled ocean-atmosphere system, including the causes of Dansgaard-Oeschger variability, glacial-interglacial cycles, and atmospheric CO_2 variation.

In an effort to address the paleoceanographic questions in a meaningful way, workshop participants discussed the suggestion by Alley (2003) that "paleoceanographers should consider following the ice-core community's lead and organize a research effort to generate a few internationally coordinated, multiply replicated, multiparameter, high time resolution-type sections of oceanic change." The group

Table 1. Location of proposed drilling site locations.

Site	Lat (N)	Long (W)	Depth (m)	Distance to land (km)	Objectives
1A	37°52,1	10°12,6	2978	123.4	Plio- Quaternary Sequence with ±700 m
2A	37°48,45	9°50,35	2266	91	Plio-Quaternary Sequence with 750–1000 m
3A	37°45,5	10°02,0	2619	108	Plio-Quaternary Sequence with 400–700 m
4A	37°33,1	10°08,8	2658	118	Plio-Quaternary Sequence with 400–800 m
5A	37°32,8	10°22,2	3559	140	Plio-Quaternary Sequence with 400–800 m

suported such an approach and proposed that IODP drilling of the Portuguese Margin could serve as a "proof of concept" for adopting an integrated strategy for sampling and analyzing IODP cores that emphasizes a truly multi-proxy approach with attention to resolution, replication, and time control. As a way forward we identified five potential drilling sites in a range of water depths that target sections with the greatest possible sedimentation rates for all time periods of interest and offer the opportunity to obtain continuous sequen-ces that are undisturbedby downslope transport (Fig. 1). In anticipation of the high sample demand for these reference sections, we would plan to drill many holes (up to six) per site to produce multiple copies of composite sections for short- and long-term sampling requests.

In addition to the paleoceanographic questions, a number of tectonics-related questions were generated by the workshop, including: (1) What is the recurrence interval of potential destructive earthquakes and tsunami? (2) What is the rheology of the area? (3) What are the interactions between fluid pressure variation and fault kinematics? Addressing these questions is vital for understanding and mitigating geohazards in this region. As the state of "drilling readiness" for the two sets of objectives is quite different and issues with the borehole observatory site will require additional time to resolve, workshop participants opted to prepare separate but parallel drilling proposals.

The first proposal is to drill the marine-type sections of millennial variability for the last several glacial cycles, known as "Shackleton sites" (to be submitted 1 April 2010). The second is a pre-proposal to address the important geohazards/tectonic concerns of this seismic region (to be submitted in either April or October 2010).

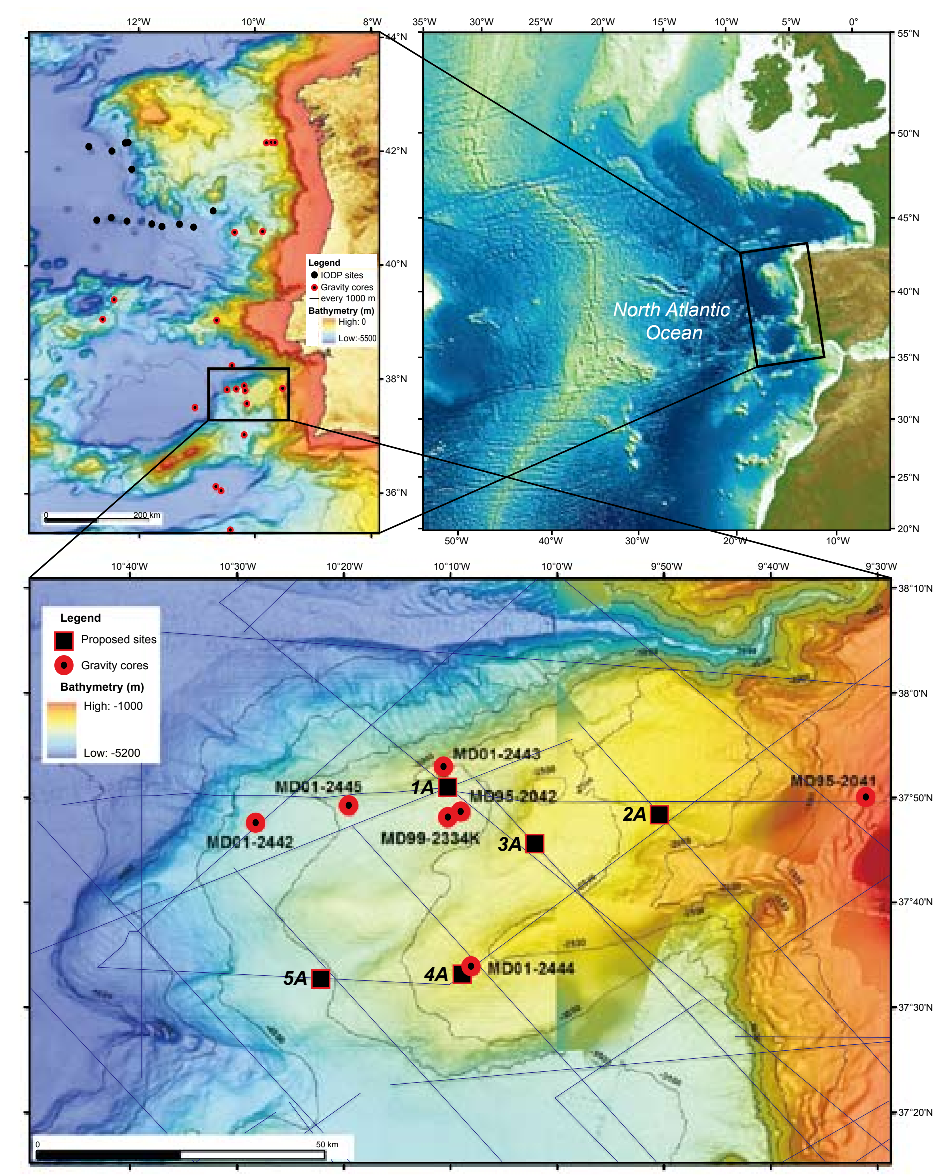

Figure 1. Locations of existing seismic lines, previously collected cores ("Shackleton sites"), and proposed site locations.

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Related Web Link

http://www.esf.org > Shackleton > Past Science Meetings

Workshop on Pliocene Climate

by Johan Etourneau and Nabil Khélifi

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The warm Pliocene epoch (5–3 million years ago) is often cited as a good analog for the near future climate because of its striking resemblance to the predictions of the "Intergovernmental Panel on Climate Change" for the next decades. Indeed, relative to today, during the Pliocene epoch, surface temperatures were 3–4°C warmer, sea level was about 5–40 meters higher, atmospheric CO_2 concentrations were relatively similar or slightly higher (~400 ± 50 ppmv), and ice sheets were restrained to Antarctica. However, since 3.0 Ma ago, the Earth's climate has undergone a major transition from a warm and relatively stable state towards cold conditions marked by amplified glacial/interglacial cycles and widespread ice sheets in the Northern Hemisphere (NHG), and to a lesser extent over Antarctica. The causes and consequences of this global climate transition—driving warm periods to "icehouse" conditions marked by "Quaternary-style" glacial/interglacial cycles—are still uncertain. Yet, they may include the interaction of several mechanisms tied to oceanic and atmospheric circulations, tectonic-, greenhouse gases-, and biological activity, biogeochemical processes, and changes in Earth's orbit.

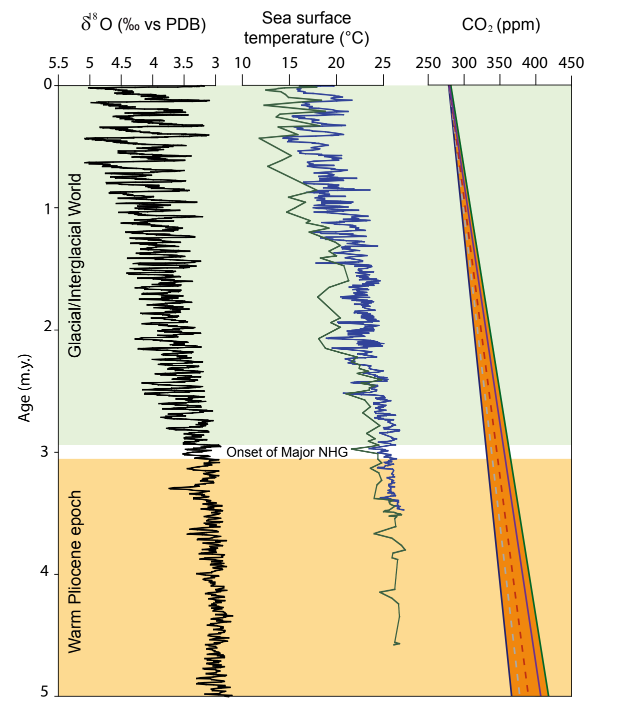

Figure 1. The Pliocene-Pleistocene climate transition illustrated by the increasing benthic $\delta^{18}O$ (ice volume) trend (Lisiecki and Raymo, 2005), the sea surface temperature cooling in the Benguela Upwelling System (Marlow et al., 2000; Etourneau et al., 2009), and the alkenone-based atmospheric CO_2 decline (Pagani et al., 2010).

To discuss the different theories explaining this major climate shift, a workshop on Pliocene climate was organized in Bordeaux (France) on 23–25 October 2009. The workshop was sponsored by the European Science Foundation through the "Magellan Workshop Series", the "Université Bordeaux 1", the "Observatoire Aquitain des Sciences de l'Univers", the "Institut des Sciences de l'Univers", and together with considerable financial support from Prof. Gerald Haug, ETH Zürich (Switzerland). In total sixty-three participants from eleven countries participated at the workshop, which was divided into two major parts. Three sessions were dedicated to talks and posters, and three sessions were devoted to group discussions. In addition, Prof. Ralf Tiedemann from Alfred Wegener Institute—Bremerhaven (Germany) and Alan Haywood from the University of Leeds (U.K.) presented keynote lectures on reconstructing and modeling Pliocene climate.

During the three days, a series of thirty-three oral presentations and seventeen posters focused on six major key issues: (1) oceanic gateways, (2) changes in Plio-Pleistocene atmospheric CO_2, (3) changes in the North Atlantic Circulation and the impact of Mediterranean outflow water on the formation of North Atlantic deep water, (4) North Pacific and southern oceanic/climatic reorganization, (5) tropical/subtropical Pacific conditions, and (6) modeling the Pliocene climate.

Related to these themes, seven discussion groups were in charge of reviewing the main causes for and consequences of the major Pliocene climate change, and to recommend new directions for future research, including drilling targets to be included in the Integrated Ocean Drilling Program (IODP) future objectives.

More specifically, the discussions addressed the following questions.

- What role could the narrowing of the Indonesian Gateway and the closure of the Panama Seaway have played on the thermohaline circulation and Pliocene climate?
- How varied was the atmospheric CO_2 through the Plio-Pleistocene climate transition?
- What may have been the major factor(s) controlling atmospheric CO_2 changes, and which impact might

Figure 2. Wind-eroded landforms in the Yadan National Geological Park, Gansu Province, China, resulting from the dryness of a paleolake over the Pliocene-Pleistocene climate transition. Decreasing regional rainfalls are supposed to be closely tied to the Himalayan uplift associated to changes in the atmospheric pattern.

the latter have had on global climate and ice sheet extension?

- Did biogeochemical cycles change in high and low latitudes during the transition from the Pliocene to Pleistocene time, and to what extent might they have impacted on greenhouse gas levels?
- How did the reorganization of the atmospheric circulation affect monsoon system variability and tropical/subtropical/polar precipitation rates over the last 4.0 Ma?
- How can we improve on the currently used models for reconstructing Pliocene climate?

The discussions gave rise to a unanimous consensus: the data spanning the Pliocene are missing in several key sectors of the world ocean, and such data are absolutely needed to further investigate what caused the climate to dramatically cool and generate widespread glaciations in the Northern Hemisphere over the Plio-Pleistocene transition.

A group was specifically tasked with collecting propositions from all participants to define near-future drilling targets. It is clear that the lack of several proxy records from key locations (e. g., bottom and sea surface temperatures, water mass origin, productivity, ocean mixing, CO_2 levels, and most importantly a reliable sea-level record covering the last 5.0 Ma) prevents the scientific community involved in Pliocene studies to further explore the causes and consequences of this climate shift. For instance, only one IODP site 806 in the western equatorial Pacific is available to constrain Plio-Pleistocene changes in the entire warm pool conditions. Also, well dated, located, and preserved ocean records for reconstructing African and South Asian climates are too scarce. Oceanic sedimentary archives from East Africa are particularly crucial for a better understanding of the links between hominid evolution and the African climate during the Pliocene.

Another challenge is the poor knowledge of the extent of ice sheets in the northern high latitudes during the Pliocene. Future IODP drilling campaigns need to be planned in the Arctic Ocean. Given the importance of oceanic gateways in controlling the global thermohaline circulation system, it was also concluded that drilling north of the Bering Strait and offshore Indonesia and Panama is also needed. In addition, to better understand the role of the northern and southern polar oceans in the Pliocene cooling, future IODP drilling should be expanded into the Pacific and Indian parts of the Southern Ocean as well, particularly around and within the polar front system.

After three days of discussions, several participants suggested that workshops on Pliocene climate become a regular event (every three years?) addressing, among other issues, the interactions between data and modeling. The workshop also strongly encouraged participants to submit proposals for future IODP expeditions targeting critical locations to understand Pliocene climate changes.

Further information about the program, talks and posters can be obtained from the workshop homepage: http://www.plioclimworkshop.com.

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Fig. 2: J. Etourneau

IODP New Ventures in Exploring Scientific Targets (INVEST): Defining the New Goals of an International Drilling Program

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Introduction

The INVEST conference, an international meeting to define the scientific goals and required technology for a new ocean drilling program, was held at the University of Bremen on 22–25 September 2009. Based on the large attendance and vigorous engagement of scientists in the discussion of new science/technology ideas, INVEST was extremely successful. Initially 400 participants were expected, but the INVEST steering and organization committees were thrilled to see a much larger number of scientists flock to Bremen to demonstrate their support and enthusiasm for the continuation of an international scientific ocean drilling program. In all, 584 participants, including sixty-four students, from twenty-one nations and >200 institutions and agencies attended the INVEST conference. Contributions to INVEST included 103 submitted white papers that were posted on the INVEST webpage (http://www.marum.de/iodp-invest.html), and breakout discussions in fifty working groups that focused on a range of topics during the course of the conference. In addition, students and early career scientists, as well as national funding agency managers and platform providers, presented a total of eighty-six posters. Interspersed with the working group and plenary sessions were twelve keynote lectures, chosen to highlight overarching themes and new directions in research and technology.

The conference was sponsored by IODP-MI, the Deutsche Forschungsgemeinschaft (DFG) and the MARUM research center. Using input from national workshops that took place in the year prior to the INVEST conference and that provided initial ideas for scientific directions and themes, the INVEST working group sessions were organized within six conference themes: 1) Co-evolution of Life and Planet, 2) Earth's Interior, Crust and Surface Interactions, 3) Climate Change – Records of the Past, Lessons for the Future, 4) Earth System Dynamics, Reservoirs and Fluxes, 5) Earth-Human-Earth Interactions, and 6) Science Implementation.

Each meeting attendee was given the opportunity to participate in three working groups: one within conference themes one through three, one within conference themes four and five, and one within conference theme six. Up to eighteen working groups met in parallel sessions. All working groups within one conference theme met to report to each other the results of the individual working group discussions. The conference theme co-chairs then met with the working group chairs and scribes to prepare a plenary presentation of the conference theme.

The steering committee, with the help of some conference session chairs, used the working group notes and plenary session presentation materials to write the INVEST conference report. The main chapters of the report are "Climate Change Impacts", "The Lithospheric Membrane: The Key Interface and Processing Zone", "Co-evolution of Life and the Planet", and "Earth-Human-Earth Interactions". In addition, several "Cross-disciplinary Research Frontiers" were identified as being important new ocean drilling themes and were highlighted in a separate section of the report. Implementation and outreach aspects are summarized in the chapters "Technology Needs and Developments" and "Outreach, Education, and Branding". "Recommendations for the New Ocean Drilling Program" is the final chapter of the INVEST report and pertains to what the community considers desirable program architecture and science advisory structure. A brief synopsis of each of these chapters is presented below. More details on the INVEST meeting structure, white papers, background material, and the complete report can be found at the INVEST website.

Climate Change Impacts

Earth's climate results from complex interactions among Earth system components, including the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Variations in these systems over short and long timescales, including the way material cycles among them (e.g., carbon cycle, hydrologic cycle), result in changes to Earth's climate. Understanding how climate has changed in the past and how it will change in the future requires understanding of how the Earth system behaves over a range of conditions. Instrumental records, collected over the last century or so, are insufficient by themselves to study long-term climate change. On the other hand, ocean drilling of sediments and corals provides a unique opportunity to acquire the high-resolution records of past change needed to examine and understand the baseline of natural climate variability against which current climate change can be compared. These records will also allow study of the behavior of the Earth system during different climate states and major climate transitions throughout the Cenozoic, as well as the origin of and mechanisms that lead to abrupt, seasonal- to millennial-scale climate changes.

Fundamental climate change questions that can be addressed by ocean drilling are outlined throughout the INVEST report. This section on "Climate Change Impacts" focuses on scientific questions that, when answered, will underpin our understanding of climate change. It explores the behavior of the climate during abrupt and extreme events, the stability of ice sheets and their relationship to sea level and coastal/shoreline processes, and the impact of regional and global climate on the hydrologic cycle. In the "Earth-Human-Earth Interactions" section, climate change questions are framed in anticipation of future conditions associated with increasing levels of atmospheric carbon dioxide. Climate change questions related to tectonics and hominin evolution are explored in the "Cross-disciplinary Research Frontiers" section.

Ocean drilling can provide unprecedented insight into climatic and oceanic processes through investigation of past rapid and extreme climate events (Fig. 1). These globally significant events represent major deviations from the natural variability of Earth's climate. Extreme events originate from perturbations in a specific component of the Earth system and typically propagate through complicated feedbacks across some or all components, allowing interconnected processes to be examined and understood. Extreme and rapid events stand out in noisy sediment-derived proxy records and are thus easy to quantify. This allows investigation of dynamic system behavior, such as tipping points and thresholds. Ocean drilling remains the only means to reconstruct, at medium to high temporal resolution, the global climate evolution of the Earth system throughout the Cenozoic. Large amplitude perturbations often mark epoch boundaries and provide one of the main avenues to investigate large-scale events, including those that involve extreme climates, ecosystem turnover, and biodiversity evolution. Drilling is also the only means to study how rapid climate phenomena that occur on seasonal to millennial timescales, such as the El Niño Southern Oscillation or Dansgaard-Oeschger cycles, behave under different boundary conditions.

Only ocean drilling can provide the geologic perspective necessary to understand ice-sheet dynamics and the resulting impacts to sea level and shorelines. Over the past 100 m.y., sea-level change reflects global climate evolution from a time characterized by ephemeral Antarctic ice sheets (100 Ma to 33 Ma), to a time when large ice sheets occurred primarily in Antarctica (33 Ma to 2.5 Ma), and finally to a world with large Antarctic and Northern Hemisphere ice sheets (2.5 Ma to present). Over the last ~800 kyr, the cyclic growth and decay of continental ice sheets induced rapid sea-level change with maximum amplitudes of 120–140 m at intervals of ~100 kyr. Ice volume fluctuations can be inferred from eustatic

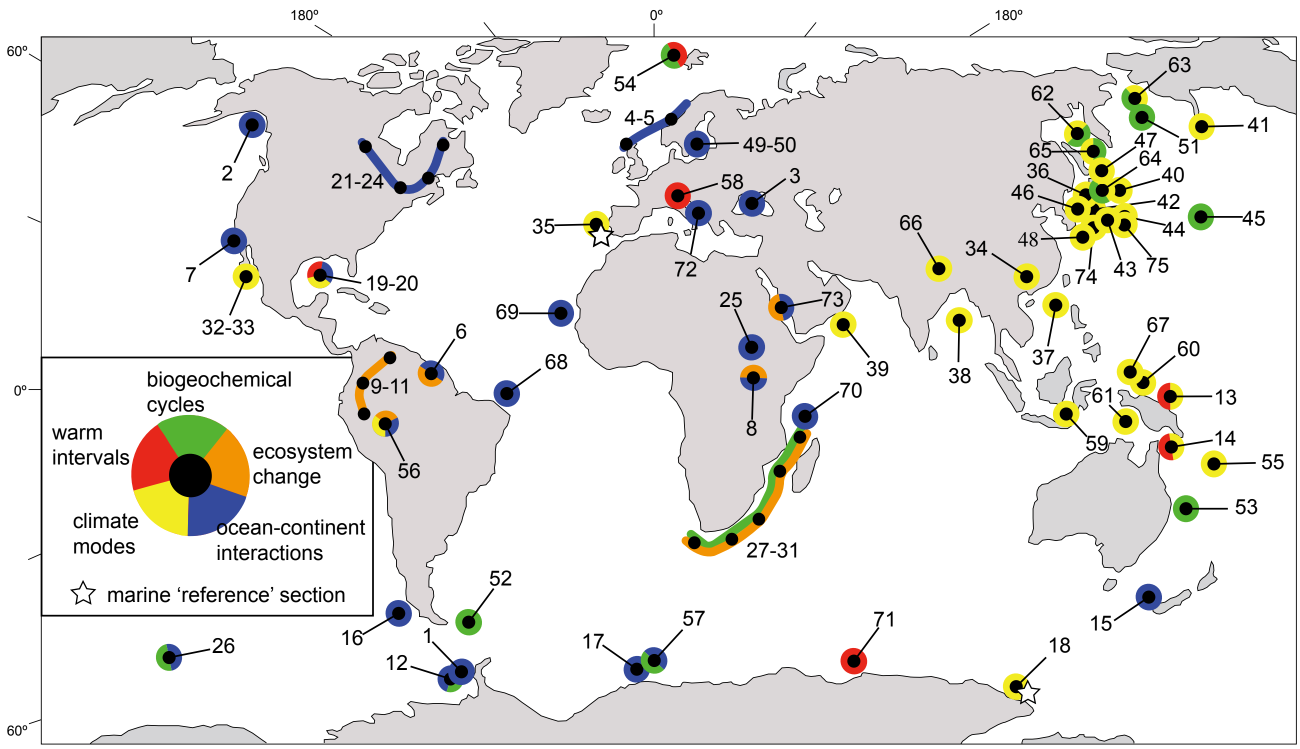

Figure 1. Compilation of potential drilling sites proposed by workshop participants to address the scientific themes 'Warm intervals through time', 'Ocean-continent interactions', 'Biogeochemical cycles', 'Ecosystem change', and 'Climate modes'; from Thurow et al., (2009). Site numbers are linked to information that can be found in Appendix 1 at http://high-resolution.icdp-online.org.

sea-level curves deciphered through comparison of regional sea-level records from various latitudes and tectonic settings. For example, observations from sites distal to glaciated regions (i.e., the "far field") are less affected by isostatic deformation and therefore better suited to constrain glacial eustasy, whereas sea-level data from sites proximal to former ice sheets (i.e., the "near field") provide information on local ice-sheet dynamics.

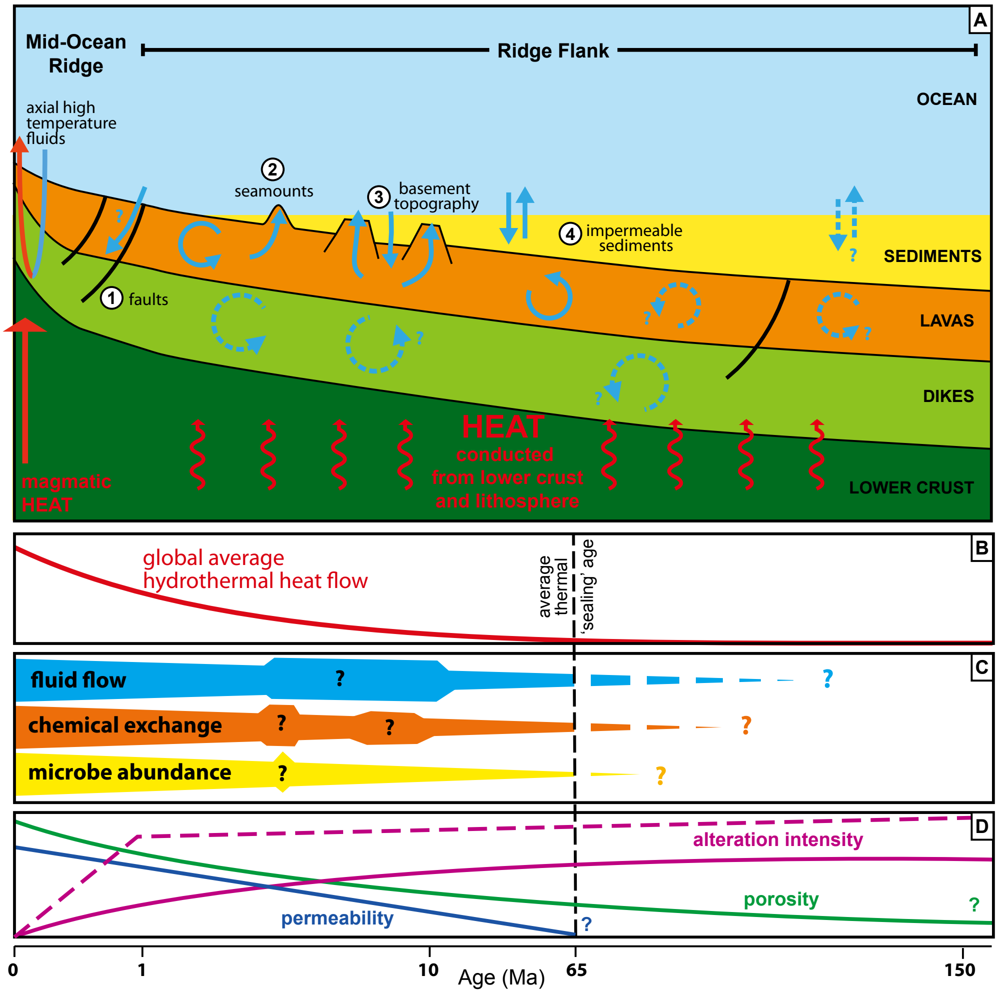

Figure 2. Diagram showing the predicted changes in crustal properties during aging (from Teagle et al., 2009). [A] Parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as faults, seamounts, basement topography and impermeable sediments. Arrows indicate heat (red) and fluid (blue) flow. [B] The difference between the average measured conductive heat flow and that predicted from conductive cooling plate models. The calculated global hydrothermal heat flow decreases to zero, on average, by 65 Ma. At this age the crust is typically assumed to be 'sealed' to hydrothermal circulation. [C] How parameters such as basement topography and sediment thickness affect fluid-flow, chemical exchange, and microbe abundance in the crust during the aging process remain undetermined. The hydrological, physical, chemical, and biological evolution of hydrothermal circulation through the ridge flank could be investigated across a ridge flank. [D] The controls on the intensity and style of hydrothermal circulation could be investigated by the measurement of multiple parameters such as porosity, permeability, and alteration mineralogy.

Understanding the processes that control changes in the hydrologic cycle is one of the most pressing issues in climate change research because changes in precipitation and evaporation impact the salinity/density distribution in the surface ocean, ecosystems on land, floods, aridification, water resources, and climate-vegetation feedbacks. A comprehensive examination of climatic controls on the hydrologic cycle requires the study of long-term trends and variability over a range of climatic states. In fact, even small global temperature changes impact the energy balance in tropical regions, resulting in changes in evaporation and storm and hurricane activity. In the mid-latitudes, changes in atmospheric thermal gradients can impact atmospheric circulation, the location of storm tracks, and the intensity of storms. There is an urgent need to understand controls on the Intertropical Convergence Zone, climate oscillation modes and their behavior during different mean climate states, wind-driven upper ocean circulation and its coupling to atmospheric forcing, monsoon dynamics, and the relationship between precipitation patterns, density stratification, and biogeochemical processes, to name a few. Future ocean drilling is absolutely necessary to obtain the records needed to constrain past changes in surface ocean conditions associated with major changes in large-scale atmospheric circulation. This must be complemented by continental climate reconstructions obtained from drilling sediments on continental margins and on land. Finally, ocean drilling studies focused on the hydrologic cycle should be used to validate regional climate models used to predict climate change and its associated impact on water resources.

The Lithospheric Membrane: The Key Interface and Process Zone

Our tectonically active planet evolves by chemical and physical changes from the core and mantle, through the lithosphere to the ocean and atmosphere. Flow of material and energy among these reservoirs drives both gradual changes in the Earth's structure and composition, as well as extremely rapid volcanic events that impact Earth's environment. The lithosphere is the major interface between the solid interior of the Earth and the exterior hydrosphere/atmosphere/biosphere (Fig. 2). Quantifying the fluxes mediated by the lithospheric processing zone is crucial for understanding the state and evolution of our planet, and ocean drilling provides a key tool in this endeavor.

From direct sampling we can examine the fundamental steady-state processes of ocean crust accretion, plate aging, and recycling, as well as intermittent events such as eruptions of large igneous provinces and rifting of continents. These processes affect the presence and state of resources that society depends upon—including sources of energy, fresh water, and nutrients—but they also create deleterious effects on society through earthquakes, tsunamis, and volcanic eruptions.

It is timely to stress that many of the things to be learned about the "lithospheric membrane" of the Earth are of great societal relevance. Understanding initiation of plate boundaries and evolution of plates is fundamental to learning how the Earth works and how the continents we live upon were formed and evolve. Plate boundary formation and related volcanism have impacted past climate and may yield information about agents of climate change. Rifted continental margins host major hydrocarbon reservoirs that are an essential energy resource. Subduction zone hydration-dehydration cycling affects earthquakes and volcanic hazards. Hydrothermal systems form polymetallic sulfide deposits of potential economic interest and also host microorganisms that may be useful for bioengineering. Finally, the ocean crust provides vast opportunities for CO_2 capture and storage.

Understanding hydrothermal transfers of heat and mass between the lithosphere and hydrosphere/atmosphere on a global scale has been identified as a high-priority overarching research question. Seawater circulation facilitates microbial growth within the ocean floor and is critical to the transport and distribution of microorganisms; however, the size, activity, and connectivity of the intracrustal oceanic biosphere and its influence on global geochemical and biogeochemical cycles are unknown. Investigation of the coupling between hydrogeological, geochemical, thermal, mechanical, and biological processes and their relationship to the architecture and physical nature of oceanic lithosphere is essential. Of primary importance is addressing the nature of the Mohorovičić discontinuity (Moho), a first-order geophysical interface within our planet, which is uncertain in slow-spreading mid-ocean ridge environments. It could be an igneous boundary or a serpentinization front—a difference with profound consequences for the chemical and rheological properties of the lithosphere. As much as one-quarter of the seafloor exposed at slow-spreading mid-ocean ridges is a heterogeneous assemblage of peridotite and gabbroic lithologies, which is hydrothermally more reactive and undergoes greater changes in physical properties than layered basaltic crust. To understand ocean-crust composition, structure, and evolution, it is essential to drill a complete crustal section across the Moho and into the shallow mantle at a fast-spreading ridge. Complete sampling is also necessary to provide *in situ* confirmation of geophysical imaging of the ocean crust.

When oceanic lithosphere is recycled during subduction and plate collision, sediments may be scraped off, and ocean crust can be accreted to a continent or island arc. Deep in subduction zones, dehydration reactions and melting of subducting sediments and occasionally the upper crust produce continental or oceanic volcanic arcs. Both of these processes can effectively transfer crustal material, fluids, and volatiles from the geologically transient oceanic lithosphere to more permanent continental crust. Ocean drilling is a critical tool necessary to investigate the relative roles of these processes and the magnitudes of element fluxes. Of crucial importance in determination of input fluxes are reliable estimates of the chemical and mineralogical state of the subducting ocean crust. Additionally, subduction zones produce some of the most significant geologic hazards to society including the highest magnitude earthquakes, the greatest tsunamis, and the most explosive eruptions.

Formation, hydrothermal alteration, and subduction of ocean crust generate secular chemical and physical changes throughout the crust and mantle, as well as in the ocean-atmosphere system. Large igneous provinces and hot spot trails are profound examples of massive mantle-crust exchanges and how these vary in time and space. At intermittent intervals, the emplacement of oceanic plateaus and formation of volcanic rifted margins produce significant chemical effects in the ocean and atmosphere. Particularly intense periods of volcanic activity appear to correlate with long-term changes in geodynamic behavior, which could involve interactions between the core and the deep mantle.

Many questions still need to be answered for us to better understand the Earth system. To address these we need to quantify fluxes and interplay within the mantle-crust-ocean system (physical, chemical, and biological) and monitor fault-driven processes. We also need to obtain a better understanding of the components of a subduction zone system that control seismic behavior, which in turn affects the level of hazard posed by the plate boundary. Ocean drilling will continue to significantly contribute to our understanding of these processes.

Co-Evolution of Life and the Planet

Scientific ocean drilling is poised to offer transformative advances to disciplines within the life sciences and provide insight into how life operates and interacts with Earth processes at and below the seafloor, both today and in the past. In particular, the study of paleoenvironmental controls on marine paleoecosystems through the Cenozoic and of extant life in rock and sediments can best be studied through ocean drilling.

Exploration of deeply seated microbial populations has revealed active, extant populations of microbes down to 1.6 km depth. These sedimentary and crustal habitats are vast in scale, physically and chemically diverse, and together represent the largest biome on Earth. A major challenge in the study of subseafloor life is the need to develop a more comprehensive understanding of the microbes that live there. Future research should reveal the biodiversity of the deep biosphere (Fig. 3), as well as the degree to which it is connected to surface biomes. Metagenomics, observatories, and other emerging technologies will play a significant role in the advancement of our understanding of the function and form of extant life in the subsurface.

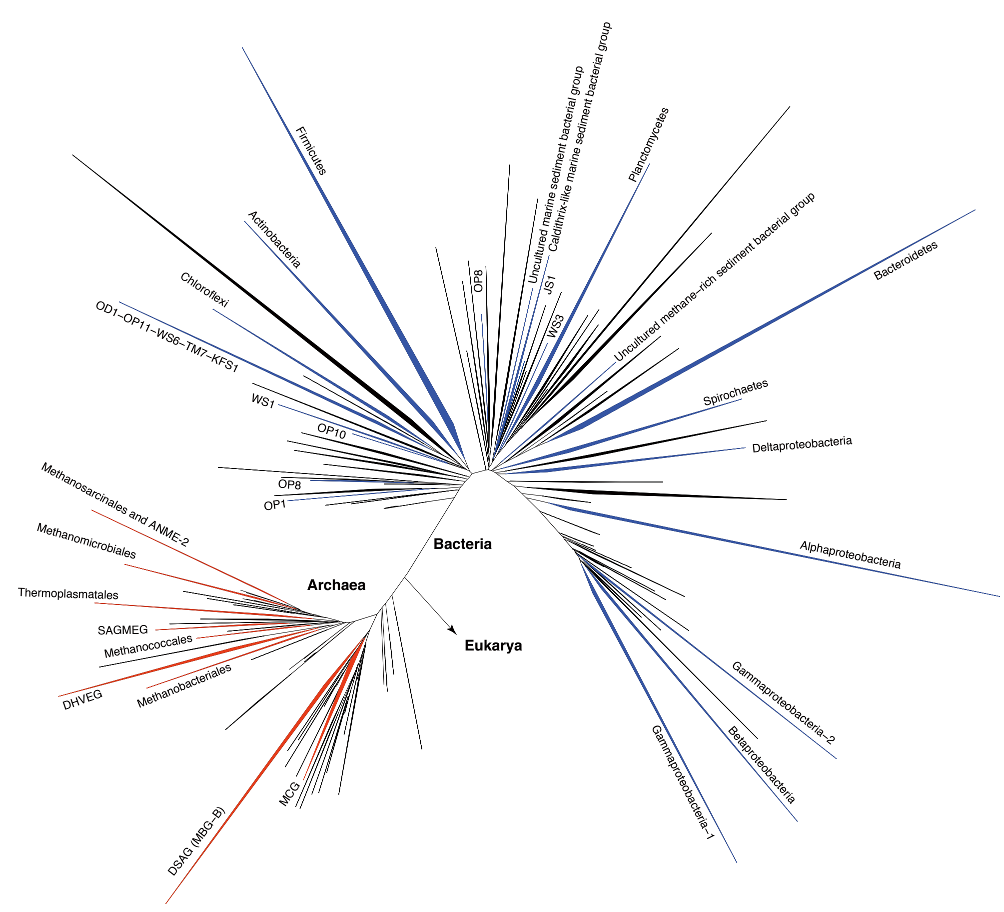

Figure 3. Phylogenetic tree of Archaea and Bacteria based on 16S rRNA gene sequences (from Inagaki, 2010). The red and blue branches represent archaeal and bacterial phyla, respectively, and include sequences frequently detected from the deep subseafloor biosphere.

Advances in our knowledge of subsurface life from past ocean drilling have principally arisen as opportunistic ventures, where a microbiologist would sail on an expedition focused on other scientific objectives. This has resulted in a significantly skewed data set. This view can be changed in the future by utilizing both opportunistic and targeted drilling expeditions for deep biosphere research. A legacy sampling program would also fill critical gaps and lead to a more comprehensive understanding of the largest biome on Earth.

New approaches and dedicated expeditions will also reveal the physiological function and activity of the deep biosphere and provide a quantitative first-order understanding of the rates and magnitude of the biogeochemical processes that occur there. How these processes impact elemental cycles of carbon, nitrogen, iron, sulfur, etc. are generally not known. This presents an enormous challenge to understanding, at a very basic level, the global implications of the presence of deep ecosystems. Does this biosphere impact Earth processes such as energy and carbon cycling, and can a better understanding of its function help solve global redox and carbon budgets? To meet these challenges new drilling and sampling are required to obtain high-quality fresh samples critical for microbiological and biogeochemical study. Research on the deep subseafloor biosphere has the potential to address urgent questions about energy creation, climate change, and the nature of evolution of life on Earth over geologic time.

Important emerging fields within paleontology are the study of systems ecology and biotic response to major environmental forcing (such as climate change). Drilling is needed to better understand how ecosystems influence and respond to their environment on different timescales in order to predict how populations will respond to present and future global change. High temporal resolution records across paleogeographic gradients and through time can thus be used to study the processes that generate and destroy biodiversity.

Human-Earth-Human Interactions

Geohazards

A top priority for the new drilling program should be the study of geologic hazards. Geology touches society directly through earthquakes, tsunamis, and landslides, and drilling can provide key constraints. Ocean drilling can be combined with other onshore and offshore national and international geohazards programs to provide knowledge for hazard assessment and mitigation of earthquakes and tsunamis that have the potential to directly impact the majority of the world's population, as well as for submarine slides that are of great concern to subsea and coastal infrastructure.

Research over the past decade indicates that old models of only two types of failure, stick-slip and creep, are incorrect. Slow-slip events, very low frequency earthquakes, and tsunami earthquakes are part of the stress-strain cycle (Fig. 4), and with the recent Haiti earthquake (Mw 7.0) there is recognition that even modest events can potentially cause a devastating loss of life. Specific queries for a drilling-based study of earthquake geohazards include the following: What is the nature of large-slip zones in earthquakes? What controls the size of earthquakes? Are very large destructive earthquakes governed by the same processes as small earthquakes? What are the characteristics of the earthquake repeat cycle? What causes tsunami earthquakes? What controls the range of tsunami efficiency generated by different earthquakes? Are earthquakes on different types of faults (e.g., subduction megathrusts vs. plate-boundary strike-slip faults) fundamentally the same or different? To answer these questions requires drilling using a range of platforms, sampling, and logging strategies, integration with observatories and modeling, and collaboration with onshore studies.

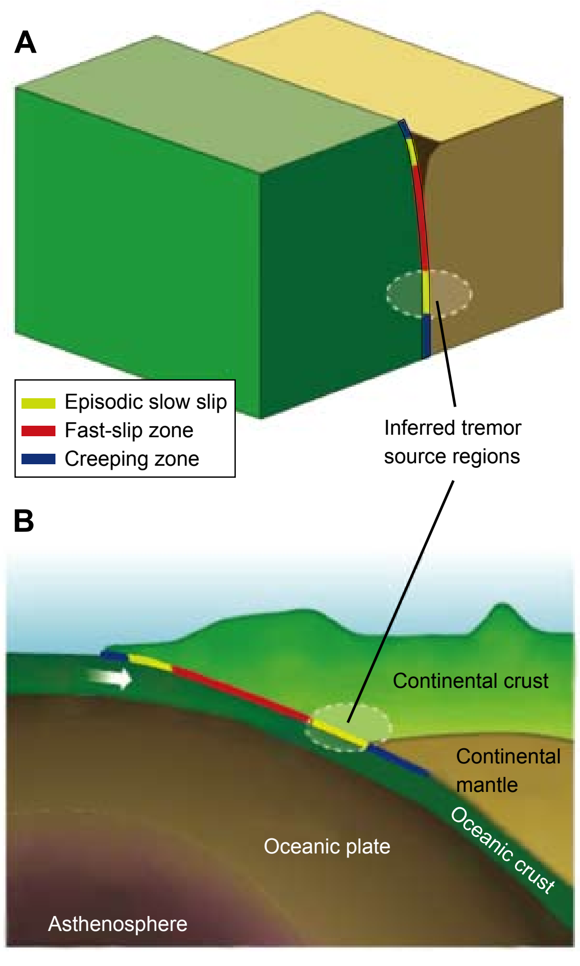

Figure 4. Locations of brittle fast-slip (seismogenic) and slow-slip zones: [A] Vertical strike slip fault; [B] Subduction zone. The new paradigm in earthquakes includes not only classically understood locked zones that break in fast slip producing earthquakes and adjacent creeping zones that nearly continuously deform without generating earthquakes, but also faults with episodic slow-slip zones that produce tremors. Additionally some subduction zones generate tsunami earthquakes that produce inordinately large tsunamis compared to the size of the earthquake (from Kanamori, 2008).

Submarine landslides occur at a wide range of scales and settings. They often comprise distinctive mass-transport deposits recognized on the seafloor or in seismic reflection profiles. Small-scale submarine landslides are relatively frequent. They have displaced oil rigs, damaged pipelines, broken deep-sea communication cables, and devastated segments of coastline. Large- and small-slide events along coastal zones also create local, destructive tsunamis. A variety of triggers have been implicated in the initiation of submarine landslides, including earthquakes, sea-level change, and gas hydrates. There are important questions for examining this geohazard. How safe is the ocean floor? What causes and triggers submarine landslides? What are the frequencies and magnitudes? Is there a size-frequency relationship to submarine landslides? What is the relationship between climate change and submarine landslides? What is the tsunamigenic potential of past and future slides? Can and do gas hydrates cause seafloor instabilities? Can submarine slides cause significant hydrate dissociation? To study these processes requires drilling into past slides and into slide-prone areas to examine rheologic, hydrologic, lithologic, and geotechnical controls on slope stability through sampling, logging, and monitoring.

Exploring the Future, Anticipating the Transition to a High pCO_2 World

Increasing atmospheric carbon dioxide content (pCO_2) is the main driving force for projected future climate change. One of the primary goals of climate-change research is to quantify the Earth's *equilibrium climate sensitivity*, which is a measure of the climate-system response to sustained radiative forcing caused by changes in atmospheric greenhouse gas contents. Although it is defined as the equilibrium global average surface warming following a doubling of CO_2 and greenhouse gas equivalent concentrations, a broader definition would include the sensitivity of the entire Earth system to feedback processes that operate over a wide range of timescales. Phenomena that affect these processes include the carbon cycle, cloud cover, albedo, glacial processes, deep-ocean circulation, weathering, and acidification. Climate sensitivity may be non-linear (feedbacks affected by feedbacks), may differ regionally (such as at high latitudes where sea-ice albedo and other feedbacks may amplify climate change), and may affect the characteristics of climate variability (e.g., the response of climate to perturbations or external forcing in a warm-climate compared to a cold-climate state).

Ocean drilling can deliver unique data necessary to quantify climate sensitivity in the past (Fig. 5) and contribute to understanding the feedback processes that need to be included for successful modeling of this topic of great societal relevance. Ocean sediments contain records of past temperatures, ocean chemistry, and pCO_2 from a wide range of boundary conditions and time scales inaccessible by modern, historical, or ice-core records. In particular, continuous high-fidelity records from times with pCO_2 levels higher than today are only obtainable through drilling ocean sediments deposited during warm intervals of the past. As such, ocean drilling provides the means to answer some of the key questions related to the quantification of climate sensitivity.

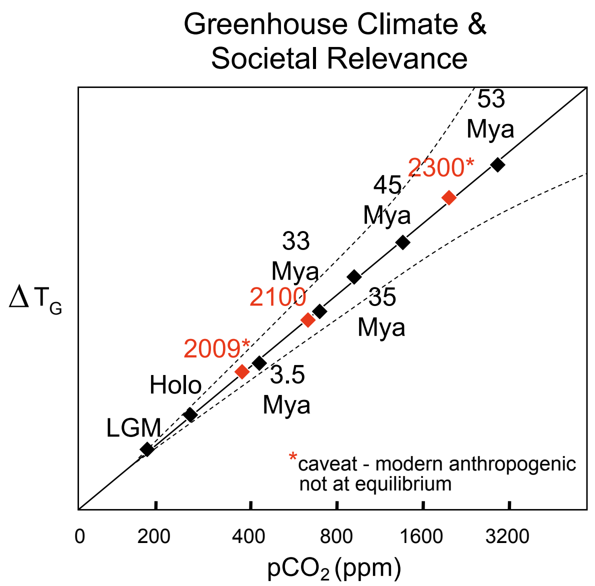

Figure 5. Schematic diagram showing the potential of the geological record to constrain climate sensitivity estimates across a range of pCO_2 values. Ocean drilling will provide observations of global temperature change ΔT_G as a function of atmospheric pCO_2 for past climates that can be compared to future predictions (Jim Zachos, personal communication during INVEST meeting; red numbers indicate calendar years now and in the future, whereas the black indicates ages in the past). For progressively higher pCO_2, possible geological analogues are found further and further back in time.

Increasing atmospheric CO_2 levels will not only cause climate to change, but will also lead to ocean acidification, known as "the other CO_2 problem". Acidification will affect bio-calcification, oceanic ecosystems, and carbon-cycle feedbacks. But, in the face of increasing pCO_2, carbon-cycle feedbacks are as uncertain as the climatic response. Ocean drilling has already played a major role in framing the current concern about ocean acidification. Although ice-core records indicate that atmospheric pCO_2 changes have only varied within a very narrow range during the past ~800,000 years, archives from times of significantly higher pCO_2 can only be obtained through ocean drilling. These records provide the means to answer some key questions about the acidification process and the timescales over which the ocean is buffered. Ocean drilling will deliver key records of lysocline shoaling, atmospheric pCO_2, carbonate ion concentrations, and biotic responses to changes in ocean acidity in order to quantify the feedbacks and enhance predictions of ocean acidification and its impacts. As such, ocean drilling can make a substantial and unique contribution to this field of immediate societal relevance.

Another urgent avenue of climate-change research is the study of factors that impact rates and amplitudes of sea-level change. The response of ice sheets (and thus sea level) to climate change is difficult to constrain because of the complexity, size, and relatively slow response of ice sheets. Since instrumental records of sea level extend back only about 150 years, refinement of predictions of sea-level rise clearly rely on past high-resolution records of the rates and magnitude of rapid sea-level change.

During glacial-interglacial transitions known as terminations, ice volume decreased, and temperatures, greenhouse gas concentrations, and sea level (magnitude >100 m) increased abruptly. Those periods are therefore regarded as potential analogues for future rapid sea-level rise and coeval abrupt climate change. The reconstruction of rates and magnitudes of sea-level rise during several terminations may help to model ice-sheet dynamics, clarify the mechanisms and sources of catastrophic ice-sheet collapse, understand suborbital climate variability, and determine the timing and volume of meltwater release under varying thermal regimes during deglaciations. In addition, gaining a much better understanding of the dynamics and sensitivity of Greenland, West Antarctic, and East Antarctic ice sheets to climate change during past warm periods is only attainable through ocean drilling, and is critically important to validating and improving ice-sheet and climate models used to predict future sea-level changes.

Cross-Disciplinary Research Frontiers

Extreme Events

Earth history, on the human and the geologic timescales, is punctuated by extreme events. Increasingly, we have discovered that intermittent, abrupt departures from stable, steady-state conditions can have major impacts on the Earth's environment, the evolution of life, and global biogeochemical cycles. The study of extreme events links many high priority science goals, crosses several broad themes, and will answer fundamental questions about evolutionary processes, and thresholds in the Earth system that, if passed, lead to dramatic ecosystem responses. For example, the processes that dictate changes in biodiversity, the oceanographic and climatic drivers of ecosystem assembly and change, speciation, and extinction can be studied through drilling of extreme events such as mass extinctions and hyperthermals. Bolide impacts and episodes of catastrophic volcanism are examples of abrupt perturbations that have left geologic records whose study will address these issues.

Future drilling can play a vital role in improving our understanding of impacts and their role in Earth's history, particularly through comparison of impacts that caused mass extinction events (e.g., the 65.5 Ma Chicxulub impact) to other large impacts that only caused minor perturbations (e.g., the 35 Ma Chesapeake Bay impact). Identifying the critical factors that lead to global environmental devastation (e.g., the energy of impact, the chemistry of the target rocks, additional environmental stresses, or the vulnerability of life at the time of impact) is possible through ocean drilling of the impact structures and the sediments containing critical fossil and environmental-proxy evidence.

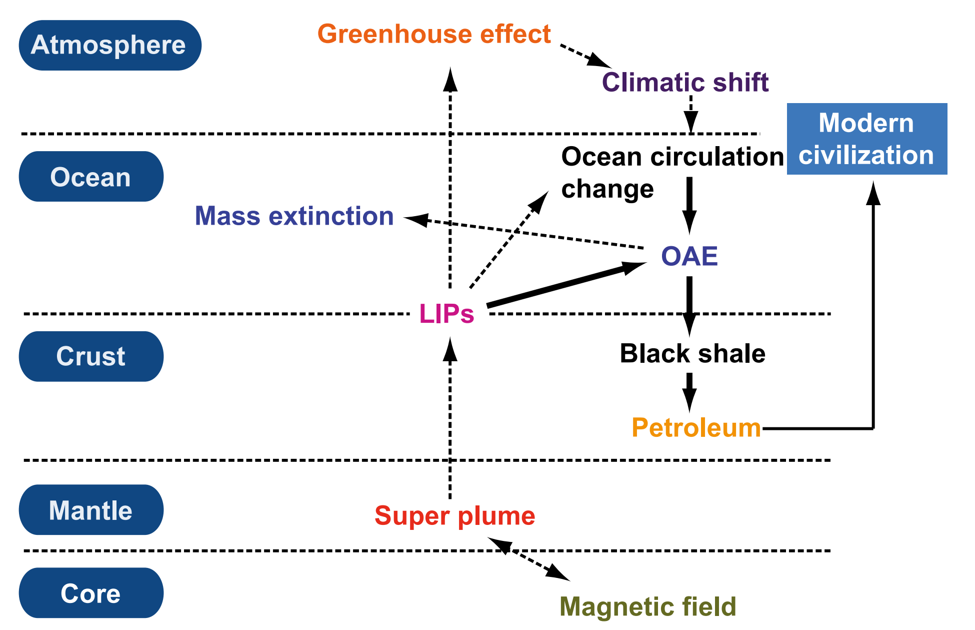

Figure 6. Proposed interconnections between reservoirs and fluxes within the Earth system during extreme volcanic events (Naohiko Ohkouchi, personal communication during INVEST meeting). The emplacement of large igneous provinces (LIPs), an expression of the Earth's interior behavior, could explain episodes of enhanced greenhouse gas input to the atmosphere and subsequent climatic and ocean circulation changes that lead to Oceanic Anoxic Events (OAEs). OAEs are extreme oceanic events marked by enhanced organic carbon burial and related biological impacts.

A fundamental process within the solid Earth is intermittent whole-mantle overturn that results in periods of eruption of large igneous provinces (LIPs) (Fig. 6), high seafloor spreading and associated arc collisions, and sea-level highstands. This mode was last prominent during the Cretaceous to early Tertiary Periods (135–55 Ma) when extraordinary eruption rates produced large igneous systems on both continents and in ocean basins. The rate, volume, and duration of these events need to be constrained to understand the geodynamic mechanisms for their origin and their potential environmental impacts, including mass extinctions, rapid global warming, ocean acidification, and oceanic anoxic events. LIPs are extreme mantle-melting and volcanic events that can be studied to answer questions about geodynamic models whose critical distinctions are magma flux through time, geochemical variability, and internal architecture—all of which are best addressed by drilling to obtain direct volcanic samples and far-field, high-resolution marine sedimentary sections.

Hominin Evolution

Scientific ocean drilling can transform our understanding of how African climate change affected early human evolution. Key evolutionary events occurred near 3.0–2.5 Ma and 2.0–1.5 Ma that effectively shaped the characteristics that define us as human: bipedalism, exceptionally large brains, and the construction of increasingly sophisticated stone tools. Environmental hypotheses for early human evolution suggest that changing African climate altered the ecological composition of a landscape, which led to specific faunal adaptation or speciation pressures that resulted in genetic selection and innovation. Where hypotheses differ is in the proposed role of climate change in natural selection. The Savannah Hypothesis states that the evolution of African mammalian fauna, including early hominins, was primarily linked to the progressive expansion of more open grassland conditions. The Turnover Pulse Hypothesis is the variant of this idea that focuses on bursts of biotic change initiated by progressive shifts toward greater African aridity at approximately 2.8 Ma and 1.8 Ma. The Variability Selection Hypothesis suggests that changes in the amplitudes of orbitally controlled African climate variability, linked to the eccentricity modulation of precessional monsoonal cycles, may have been an important genetic selection criterion. To test these hypotheses, fundamental questions concerning the timing, nature, and causes of African climate variability must be answered. Drilling targets are margin sediments that reflect the subtropical African geographic domain where hominin fossils are found, including South Africa, Tanzania, Kenya, and Ethiopia. Ocean drilling to obtain records from these regions will likely revolutionize our understanding of the timing and causes of African climate changes and allow us to test the hypothesized role of past climate changes in shaping the course of human evolution.

Climate-Tectonic Linkages and Feedbacks

Climate and plate tectonics are two forces that shape the Earth in concert; examining the interplay between climatic and tectonic processes will advance our understanding of both. Fundamental questions regarding tectonic-climate linkages can be answered by ocean drilling in conjunction with continental studies. Future studies should focus on how the changing configuration and topography/bathymetry of the continents and oceans influence ocean and atmospheric circulations and biogeochemical cycles, as well as how orogens respond to significant climate shifts such as the onset of Northern Hemisphere glaciation, the Mid-Pleistocene Transition, and the development of the Indian monsoon. Other avenues of research should investigate how tectonics influences discharge of freshwater, nutrients, and sediment from the continents to the ocean and how these affect the biota and biogeochemical cycles on continental margins and in marginal seas. The potential impact of small rivers, groundwater, and eolian transport on global freshwater, nutrient, and sediment budgets also needs to be quantified. Future ocean drilling should focus on capturing a complementary array of continental margin and fan records, including Arctic and Antarctic deposystems; exhumation history; terrestrial climate/vegetation changes; sediment, nutrients, and carbon budgets; and freshwater discharges for the areas of the Earth with the highest fluxes. Such a strategy will undoubtedly advance our understanding of the feedbacks between tectonics and climate and their combined influences on the Earth's surface.

Technological Needs and Development

To achieve novel scientific ocean drilling objectives will depend on improved drilling capabilities such as enhancing depth penetration, improving core recovery and quality, coring in high-temperature and high-pressure environments, coring in shallow water margins, coral reefs, and sea-ice covered regions (e.g., such as with the planned Research Icebreaker *Aurora Borealis*), and preventing magnetic, chemical, and microbiological contaminations. Overall, the next phase of the scientific drilling program will require significant and even more coordinated engineering efforts.

One of the most significant technological requirements is the measurement of the intrinsic and/or ephemeral properties of cores and boreholes. *In situ* measurements of redox state, chemical compositions, physical parameters, pH, and microbial populations and their activities are absolutely necessary. Newly developed (or improved) logging sensor tools, *in situ* sampling/monitoring devices, and *in situ* microbial colonization systems will be needed to achieve multidisciplinary scientific objectives through borehole observatories and experiments. Real-time hydrocarbon gas monitoring systems that include stable isotope measurements should also be deployed in platform laboratories. Novel and/or improved analytical technologies for quick, high-resolution measurements of temperature-, redox-, and oxygen-sensitive chemical and microbiological components must be developed for use on recently acquired cores, since exploration of high-temperature hydrothermal systems and the deep, hot biosphere has great potential to increase our understanding of the co-evolution of life and the planet. In addition, onboard measurements of physical, chemical, and biological properties of cores are extremely useful for real-time decisions necessary to meet drilling goals.

The development of a high-pressure- (and -temperature) coring system is required for various geochemical and biological reactions because the pressure limit of the currently available high-pressure-coring system is up to 25 MPa, which is not enough for high-pressure gas fields or deep coring (>2500 meters below the sea surface). Furthermore, once core under high pressure and temperature reaches the surface, an onboard high-pressure core transfer system equipped with multiple (micro-) sensors, gas and fluid extraction ports, tracer injection systems, and a mini-core sub-sampling system is needed.

Subseafloor microbes proliferate in narrow niches and vary over local fluid-flow pathways used to transport energy and nutrients, hence high-resolution microbiological sampling is necessary. We need to develop onboard sub-sampling strategies for quick identification of microbially interesting zones and high-resolution sampling capabilities while monitoring and minimizing contamination. Furthermore, the non-destructive identification of core quality and structures (through X-ray CT scanning) is a high priority for future microbiology/biogeochemistry-dedicated drilling expeditions. For high-throughput and high-resolution onboard analyses, computer automated systems, such as the auto-extractor and the automated cell-counting microscope system using fluorescent image analysis, should be deployed.

Penetration through a complete ocean-crust section, the so-called project "Mohole", will require advances in drilling capabilities that include riser drilling capability in 4000 m or more water depth, deep penetration and recovery of crustal rocks of all lithologies, and borehole and drill bit cooling technology for high temperature (>250 °C) environments. Technological issues include improvement of riser-pipe quality and casing strings, the blowout preventer, and the mud-circulation/recovery system.

The newly developed Riserless Mud Recovery (RMR) system has great potential for use in various environments in future drilling, especially for borehole controls (i.e., stability and cooling). Combining the dual-gradient technology with RMR enables environmentally friendly drilling (i.e., clean without mud pollutants to seawater) access to deeper environments and areas previously not drillable by riserless drilling. The RMR technology is directly applicable to all IODP platforms.

Improving core recovery and quality is the fundamental challenge for all drilling environments. Core recovery and quality depend on factors such as depth, temperature, fluid pressure, and lithology, as well as the design and performance of drilling and coring tools. In previous drilling experiences, poor core recovery has plagued (a) chert and/or shales, (b) sand and gravel layers, (c) hydrothermal deposits, (d) rubble basalts and sheeted dyke complexes, and (e) fault and fracture zones. Anticipated improvements include more accurate compensation of drill bit motion, torque, and type of cutting shoe, and operational technologies such as a feedback system of real-time drilling parameters. Other strategies, such as cuttings and side-wall coring, will increase sampling of unrecovered intervals. Borehole management (i.e., stability) requires cuttings removal and compensation of lithostatic and pumping pressures in both riser and riserless drilling modes. In addition, large diameter pipes may provide more opportunities to conduct various geophysical measurements such as pore pressures and resistivity.

Monitoring while drilling using downhole logging tools has greatly expanded our understanding of *in situ* pressure and stress conditions in the borehole. The use of logging tools during drilling or in CORKed boreholes is likely to expand in the new drilling program. Multiple-hole experiments are recommended, including injection tests and cross-borehole communication studies. Broadband and high-sensitivity sensors such as fiber-optic seismo-sensors combined with continuous data recovery should be developed and installed in active subseafloor environments. To study *in situ* conditions of high-temperature and/or high-pressure environments, the durability of logging systems to high temperature and pressure must be improved. Development of new slim-line multi-logging tools and borehole equipment is needed for all platforms. Current shipboard computational and dissemination capabilities should be more effectively integrated between software programs, database mining, and accessibility and be easily interfaced among the multiple drilling platforms and core repositories.

Outreach and Education, and Branding

Outreach refers to activities that target the general public and funding agencies. Education and educational outreach are aimed at students in primary, secondary, undergraduate, and graduate school realms. Continued coordination through IODP-MI or its successor organization is essential to achieve the best results in the arena of public outreach. A successful branding campaign will be vital to ensure ongoing public recognition of the scientific discoveries and technological achievements of scientific ocean drilling.

Branding the science and accomplishments of ocean drilling should elucidate the linkages to broader objectives or themes, and not necessarily focus on individual expeditions. As visual impression is the key for branding, web sites across the program must have a common layout to promote the impression of a truly integrated program to the scientific community and the public, and to facilitate access to information. A series of bold, clear key messages should be an important element in any branding campaign. For example, the main messages of the drilling program should emphasize the following:

- The program investigates a dynamic Earth; it is a changing, not static, planet.
- Basic science is always valuable to society.
- Scientific ocean drilling is particularly relevant to society, providing knowledge about geohazards and climate change.
- Scientific ocean drilling is on the edge of the science frontier. By exploring Earth through scientific ocean drilling, we make novel and fundamental discoveries.

Outreach and education are vital in raising the profile of the future drilling program. The program needs to employ a full-time science "translator" (scientist or science educator with requisite skills) that can effectively communicate drilling science to non-scientists. Because many ocean drilling scientists are also geoscience educators, there should be mechanisms for them to be closely involved in framing the science to be easily accessible to students and the general public. Consideration should be given to expanding successful current programs to include all international partners and to serve all audiences (undergraduates, graduates, faculty, young scientists, science teachers, etc.). Specific recommendations are (a) the development and dissemination of an archive of basic images documenting the history and goals of the drilling program; (b) admitting science educators, in addition to school teachers, on expeditions; (c) providing communications training for younger scientists on board; (d) offering early career workshops sponsored by the new ocean drilling program; and (e) developing a mentoring plan for young career scientists who go to sea on expeditions and site survey cruises. Generally, the ocean drilling program should make greater use of Google Ocean and GeoMapApp to provide the public with images and video for education and outreach. Finally, in planning the new drilling program, there should be a workshop dedicated to formulating a plan that employs innovative cutting-edge methods of science education, communication, and outreach.

Recommendations for the Architecture of a New Program

Scientific planning in the new ocean drilling program should be driven from the "bottom up", with scientists playing key roles in defining specific scientific short- and long-term goals and in advising and working directly with management, ship operators, and engineering development to execute the drilling program. The direct involvement of world-class students and scientists will keep the international ocean drilling program fresh and focused on emerging transformative topics that define the frontiers of life and earth sciences. As such, a strong science advisory structure should be a central component of the new program architecture. Furthermore, transformative science is often born from cross-disciplinary perspectives, and the drilling program must have multiple mechanisms to proactively engage scientists and students from disciplines outside of the traditional drilling community, from both academia and industry.

Because of the complex nature of an international drilling program with multiple operators and stakeholders, effective management should focus on fostering stronger international partnerships, well-integrated collaborations with other large geosciences programs, effective fundraising, and creative and efficient coordination amongst the national offices and implementation/ship operators. By working with the science advisory committees and scientific community, management should facilitate the formulation of visionary and innovative scientific goals through the life of the program.

Meeting the scientific goals of the drilling program will require flexibility. Multi-expedition, long-term missions will be required to achieve these ambitious goals. At the same time, many of the highest impact ocean drilling projects may be unanticipated and/or concise and focused. Thus, there must be mechanisms by which the new ocean drilling program can quickly respond to, nurture, and execute brilliant new ideas (identified through a peer-review system) that require ocean drilling. To implement the projects necessary to achieve transformative science will require a new ocean drilling program architecture that, by design, will have the flexibility to react quickly to new opportunities, but also to make decisive commitments to long-term complex, technically challenging projects.

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EuroFORUM 2010:

Achievements and Perspectives in Scientific Ocean and Continental Drilling

2–7 May 2010, Vienna, Austria

At the EGU 2010, a special session will be devoted to scientific drilling. The principal goals of this joint Integrated Ocean Drilling Program (IODP) — International Continental Scientific Drilling Program (ICDP) EuroFORUM 2010 are to summarize and review major scientific achievements in ocean and continental drilling with special emphasis on the European contributions to IODP and ICDP. Furthermore, perspectives and visions for drilling projects using a multi-platform approach will be tackled. Co-convenors of EuroFORUM 2010 are R. Stein (AWI Bremerhaven), U. Harms (GFZ Potsdam), H. Brinkhuis (Utrecht University), G. Camoin (CEREGE Aix-en-Provence), J. Erbacher (BGR Hannover), and U. Roehl (MARUM Bremen University). Further details can be downloaded from http://meetingorganizer.copernicus.org/EGU2010/session/2717.

The ESF Magellan Workshop Series Program

The ESF Magellan Workshop Series was launched in 2006 with the aim of nurturing and coordinating innovative marine scientific drilling proposals for European scientists to strengthen the role of Europe within the international ocean drilling community. More than fifteen workshops, ten short visit grants, and one educational program have been supported. Recent workshops include Drilling of the "Shackleton Sites" and Evolution of the Baltic Sea through the Last Glacial Cycle.

Next Workrshop:

Volcanic Basins, Scientific, Economical and Environmental Aspects

7–10 May 2010, Vienna, Austria

A Call for Workshops:

Open until 15 June 2010

All scientists who wish to contribute to the future of scientific ocean research drilling and promote new scientific drilling technologies are encouraged to submit proposals. Priority will be given to proponents from ESF Magellan member countries.

For more information please see http://www.esf.org/ or contact Jochen Erbacher (jochen.erbacher@bgr.de).

IODP Canada and ICDP Canada at GEOCANADA 2010

10–14 May 2010, Calgary, Alberta, Canada

Canadian scientists from IODP and ICDP will host a booth at the GEOCANADA 2010 meeting in Calgary, Alberta (http://www.geocanada2010.ca/). This meeting is jointly sponsored by several scientific societies including the Geological Association of Canada, the Mineralogical Association of Canada, the Canadian Society of Exploration Geophysics, and the International Association of Hydrogeologists - Canadian National Chapter.

GEOCANADA 2010 exhibit hall days are 11 and 12 May. Please visit the IODP Canada (http://www.iodpcanada.ca/) and ICDP Canada (http://www.icdp-canada.ca) booth when you are there! For more information, please contact Hélène Gaonac'h (gaonach.helene@uqam.ca).

An IODP Canada/ECORD Summer School in 2010

27 June to 12 July 2010, Quebec, Canada

Canadian scientists actively involved in IODP activities will hold a 2010 summer school on "Ocean and Climate Changes in Polar and Subpolar Environments" (image below). This event will be held in Quebec (Canada) between Rimouski, Quebec City and Montreal institutions.

The summer school will focus on paleoceanography and paleoclimatology at high latitudes and will include lectures, lab work, field work in the St. Lawrence Estuary, and field trips to the St. Lawrence lowlands.

Ph.D. students and postdoctoral fellows from ECORD countries are welcome to apply. Courses and lectures will cover geophysics, geomorphology, organic, inorganic and isotope geochemistry, physics of sediments, micropaleontology, paleoceanography, modeling of sea ice, geotechnical methods of drilling polar regions, and other topics related to Arctic and subpolar environments.

For information and registration details, please see the http://www.iodpcanada.ca/news_items/open-call-for-ecord-scholarships-2010/ or contact Hélène GAonac'h (coordinator@mail.iodpcanada.ca).

ECORD Summer School on "Dynamics of Past Climate Changes"

13–24 September 2010, Bremen, Germany

The 4th ECORD Summer School in Bremen, to be held at the MARUM-Center for Marine Environmental Sciences at the University of Bremen, Germany, aims to bring Ph.D. students and young postdocs in touch with IODP at an early stage of their career, inform them about research within this international scientific program, and prepare them for future participation on IODP expeditions. Such training will be achieved by taking the summer school participants on a "virtual ship" by exploiting the unique facili-ties linked to the IODP Bremen Core Repository (image below). They will be introduced to a wide spectrum of state-of-the-art analytical technologies and core description methods, including core logging/scanning according to IODP expedition standards. In addition, the topic "Dynamics of Past Climate Changes" will be covered by lectures and discussions with leading paleoceanographers and paleoclimatologists. The latter will include climate modelers, physical oceanographers, and researchers working on polar ice cores and lake records. This comprehensive approach—combining scientific lectures with practicals on IODP-style "shipboard" measurements—is the blueprint for the Bremen ECORD summer school series, which now starts the second three-year-cycle of ECORD summer schools covering the three major topics of the IODP Initial Science Plan. For detailed information visit http://www.glomar.uni-bremen.de/ECORD_Summer_School_2010.html.

News from the Australian and New Zealand IODP Offices

The Australian and New Zealand IODP Consortium has existed since January 2008. It is a great pleasure for Australia to be back in ocean drilling with colleagues from around the world, and for New Zealand to be a member for the first time. Recently a phase of expeditions in our own region has begun: Canterbury Basin Sea Level and Wilkes Land Glacial History (successfully completed); Great Barrier Reef Environmental Changes (started in February); South Pacific Gyre Microbiology (late 2010); and Louisville Seamount Trail (latest 2010). Port calls by the *JOIDES Resolution* in Townsville and Wellington at the beginning and completion of the Canterbury expedition provided valuable opportunities to raise awareness of IODP (image below that young participants sampling the sediments). We look forward to hosting the ship again in 2010 and 2011.

The scientific communities in both countries are enthusiastically involved in planning for the next phase of ocean drilling. For more information see http://www.iodp.org.au/.

Scientific Drilling in the Nordic Countries

The researchers network "Scientific Drilling in the Nordic Countries" has recently been funded for three years by NordForsk, the Nordic Council of Ministers' advisory board on research strategy (http://www.nordforsk.org/). The aim of the network is to consolidate knowledge and experience from past and present (and future) scientific drilling projects in Nordic countries and to propagate it to the scientific community. Scientists with experience from scientific drilling enterprises and the few experts in drilling technology within academia are located at various institutions throughout the Nordic countries. For most researchers who encounter a scientific problem that requires drilling, the knowledge resource of managing and executing drilling is not readily available; this network hopes to change that.

Workshops and excursions will be tightly coupled to ongoing coordinated scientific projects and bring together experts, experienced scientists, and novices for knowledge exchange and transfer. For more information visit the network's website at http://www.sdnc.eu/ or contact Henning Lorenz (henning.lorenz@geo.uu.se).

Canada is Back in ICDP

In 2009 the Natural Sciences and Engineering Research Council of Canada (NSERC) committed itself to supporting Canadian membership in the ICDP for the next five years, giving Canadian scientists the opportunity to continue their involvement in ICDP activities and scientific planning.

ICDP Canadian scientists currently coordinate their activities through the Canadian Continental Drilling Program (CCDP). CCDP is also supported by INRS-ETE and has its co-ordination office at UQÀM jointly with CCOD, the coordination body for Canadian activities linked to IODP (http://www.iodpcanada.ca/). CCDP is presently chaired by Pierre Francus from INRS-ETE. Further information is available at http://www.icdp-canada.ca/.

New Scientific Drilling Infrastructure in Sweden

Two years ago, the Swedish geoscientific community established a national program for scientific drilling, the Swedish Deep Drilling Program (SDDP). SDDP was able to successfully promote Swedish membership in ICDP. Furthermore, the Swedish Research Council decided to support an application for a drilling rig. The envisaged drilling platform will be capable of core drilling to at least 2500 m depth in different lithologies. The Department of Engineering Geology at Lund University will organize the management of this infrastructure. The rig is intended primarily for use in SDDP drilling projects but will be rented out to other projects. As it will be capable of drilling to depths of 2000–3000 m, this rig will complement the traditional deep-drilling platform InnovaRig of the GFZ German Research Centre for Geosciences.

U.S. Implementing Organization Adds New Talent, Restructures

The U.S. Implementing Organization of the Integrated Ocean Drilling Program (USIO) has restructured and added new talent to its team. The USIO operates the *JOIDES Resolution* and consists of the Consortium for Ocean Leadership, Lamont-Doherty Earth Observatory (LDEO) of Columbia University, and Texas A&M University (TAMU).

Ocean Leadership hired Greg Myers as the new Senior Technical Expert (Engineering and Development) and Doug Fils as the new Data Management Technical Expert. Myers will oversee USIO engineering development efforts and coordinate non-IODP funding activities. Fils will interact with IODP-Management International and the USIO to develop and implement approaches to data management needs.

At LDEO, former Scientific Ocean Drilling Vessel project manager Gerardo Iturrino is now the Manager of Engineering Services and will oversee engineering development and maintenance of shipboard and shore-based logging systems. Eric Meissner takes on the newly-created position of Senior Engineering Project Manager. Alberto Malinverno will now super-vise the Science Services group while remaining in his role of Principal Scientist.

Jim Rosser has joined IODP-TAMU as the Manager of Development, Information Technology, and Databases. Rosser brings experience as a U.S. naval commander to oversee the shipboard and shorebased IT infrastructure and the acquisition and management of data collected by the *JOIDES Resolution*. Jay Miller will serve as manager of the newly formed Technical and Analytical Services Department, which is composed of the majority of the shipboard technical support staff.

ESSAC Office Moves from France to Germany

On 1 October 2009, the European Consortium for Ocean Research Drilling Science Support and Advisory Committee (ESSAC) office moved from Aix-en-Provence, France to Bremerhaven, Germany. The new office, established at the Alfred Wegener Institute (AWI) for Polar and Marine Research, is headed by Ruediger (Rudy) Stein as the new ESSAC Chair. Jeannette (Jenny) Lezius is the new Science Coordinator. More information about ESSAC and its activities is available at http://www.essac.ecord.org/.

IODP-MI Office in Tokyo

The Integrated Ocean Drilling Program Management International, Inc. (IODP-MI) is integrating most of its activities into one single location. On 1 March 2010 the former Sapporo office moved to new IODP-MI office located at Tokyo University of Marine Science and Technology, Etchujima Campus. A small office of finances and contracts office is maintained in Washington, D.C. Following a few additional staff hires, the planned restructuring of IODP-MI has been completed. The new office structure and contact details can be found at: www.iodp.org.

Schedules

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

	ESO Operations *	Platform	Dates	Port of Origin
1	325 - Great Barrier Reef Environmental Changes	MSP	11 Feb.–late Mar. 2010	Townsville, QLD, Australia
	USIO Operations **	**Platform**	**Dates**	**Port of Origin**
2	327 - Juan de Fuca Hydrogeology	*JOIDES Resolution*	05 Jul. – 04 Sep. 2010	Victoria, BC, Canada
3	328 - Cascadia CORK	*JOIDES Resolution*	04 Sep. – 18 Sep. 2010	Victoria, BC, Canada
4	329 - South Pacific Gyre Microbiology	*JOIDES Resolution*	08 Oct. – 12 Dec. 2010	Papeete, Tahiti
5	330 - Louisville Seamount Trail	*JOIDES Resolution*	12 Dec. 2010 – 11 Feb. 2011	Auckland, New Zealand
	CDEX Operations ***	**Platform**	**Dates**	**Port of Origin**
6	326 - NanTroSEIZE Stage 2	*Chikyu*	TBD	TBD

MSP = Mission Specific Platform TBD = to be determined
* Exact dates in this time frame dependent upon final platform tender.
** Sailing dates may change slightly. Staffing updates for all expeditions to be issued soon.
*** CDEX schedule subject to OTF and SAS approval.

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

	ICDP Projects	Drilling Dates	Location
1	Lake Van	Jul. 2010–Sep. 2010	Anatolia, Turkey
2	Snake River Plain	Jul. 2010–Sep. 2011	Idaho, U.S.A.
3	Songliao Basin	Jul. 2010–Sep. 2011	NW China
4	Barberton Greenstone Belt	Oct.–Nov. 2010	South Africa
5	Dead Sea	Dec. 2010–Jan. 2011	Israel/Jordan
6	Campi Flegrei	May–Aug. 2011	Italy
7	Lake Ohrid	Jul.–Aug. 2011	Macedonia/Albania