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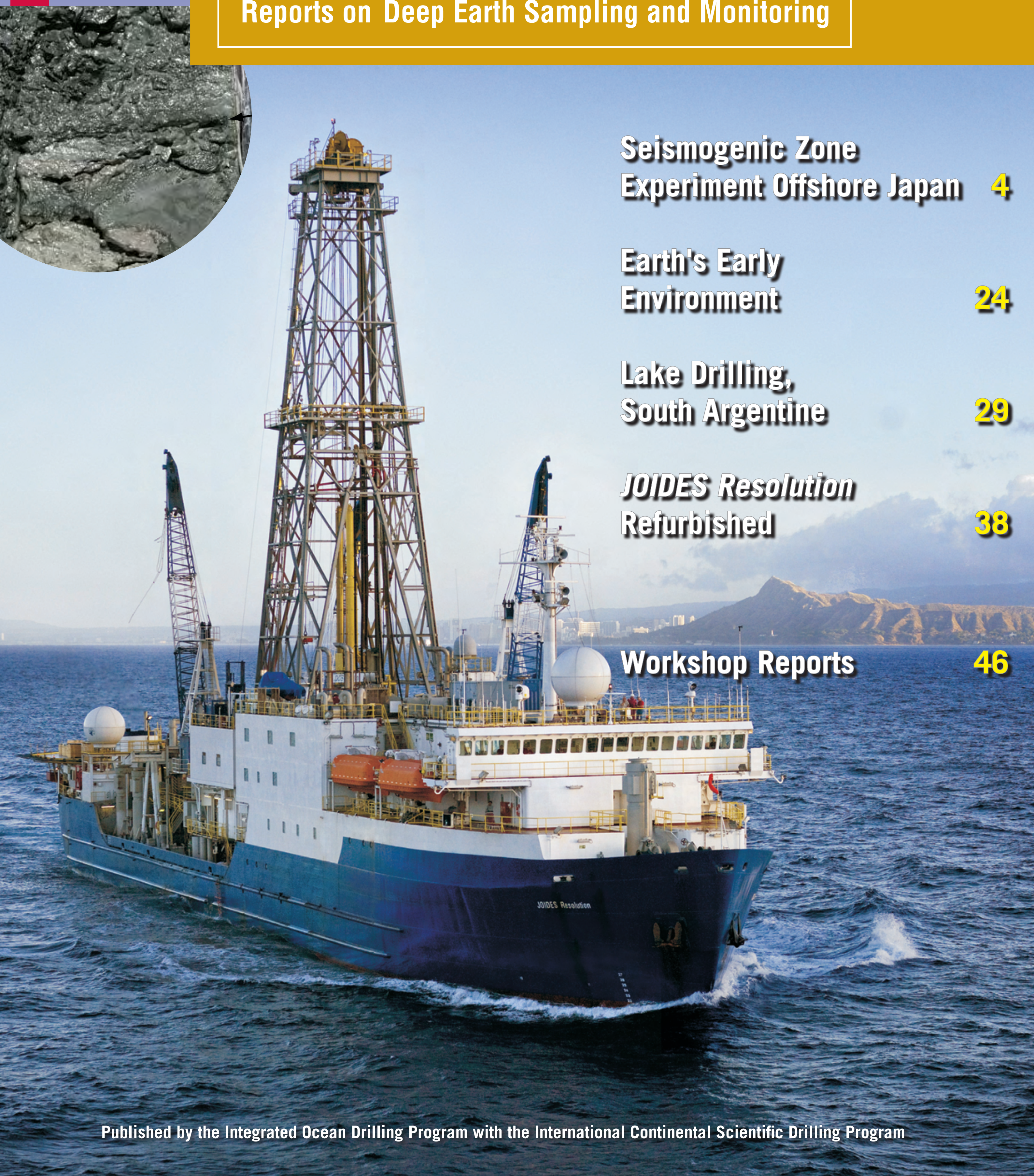
Reports on Deep Earth Sampling and Monitoring



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Editorial Preface

Dear Reader:

A survey among leading Earth scientists in Europe and the U.S.A. yields a ranking of topics in geosciences: earthquake prediction (21%), climate change (20%), origin of life (10%), deep Earth processes (9%), sustainable energy resources (7%), volcano eruption prediction (6%), and plate tectonic challenges (5%). This issue of *Scientific Drilling* reflects full accord with these key topics.

Fundamental research in support of earthquake prediction is pursued by IODP through an ambitious drilling and observatory experiment (page 4). Workshop reports address possibilities to recover ephemeral fault-zone properties immediately after large earthquakes (page 66), to drill into New Zealand's Alpine thrust fault (page 75), and to study a low-angle normal fault within the western U.S. (page 57). Regarding climate change, a report from a joint IODP-ICDP workshop addresses high resolution paleoclimate records from lakes, ice and oceans, and how these can be integrated to elucidate key climate drivers (page 46); an example is the Laguna Potrok Aike drilling campaign in southern Argentina (page 29).

The Archean Barberton Mountain Greenstone Belt in southern Africa preserves clues on early life and Earth conditions (page 24). In recent geological times, the East African Rift formed, and its basins and lakes provided environments for our ancestral hominids to develop under the influence of a variable climate and landscape. A meeting in Addis Ababa, Ethiopia addressed drilling plans to recover 6 My of environmental history, and tie this to the record of hominid evolution (page 60). A high priority of IODP is to drill the equivalent offshore marine sequence within the Gulf of Aden. However, safety issues currently prevent IODP to join ICDP in this exciting endeavor to understand our evolutionary past.

A large gathering of Earth and ocean drilling scientists will take place in Bremen on 23–25 September to discuss a new scientific ocean drilling program to replace IODP by 2013 (*INVEST*; www.marum.de/iodp-invest.html). With the legendary drilling vessel *JOIDES Resolution* refurbished and successfully back in service to IODP (page 38), and with current scientific drilling activities being well aligned with topics of high scientific and societal rank, this meeting is well positioned to define future goals. One of the five overarching themes of the *INVEST* meeting is "Earth-Human-Earth Interactions". Incidentally, a recent editorial in *Science* (17 July 2009) states that there is "urgent need to confront human-induced global environmental change". Earth scientist involved with drilling indeed seems to have their feet well attached to the ground, and ready to take on such future challenges.

The important role of the major drilling programs in providing for a holistic understanding of our global environment is also a clear message from the new president of IODP (page 83), calling for enhanced collaboration between drilling and other major research programs. Welcome to this 8th issue of *Scientific Drilling*!

Hans Christian Larsen
Editor-in-Chief

Ulrich Harms
Editor

Front Cover: The *JOIDES Resolution* departed Honolulu, Hawaii, on 9 May 2009 at the beginning of Expedition 321: Pacific Equatorial Age Transect 2. Photo Credit by WIlliam Crawford, IODP/TAMU. (See page 38)
Left inset: Core from the frontal thrust, IODP Expedition 316. The thin dark layer in the center represents major displacement. (See page 8)

Scientific Drilling

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

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

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NanTroSEIZE Stage 1 Expeditions 314, 315, and 316: First Drilling Program of the Nankai Trough Seismogenic Zone Experiment

by Harold Tobin, Masataka Kinoshita, Juichiro Ashi, Siegfried Lallemant, Gaku Kimura, Elizabeth Screaton, Moe Kyaw Thu, Hideki Masago, Daniel Curewitz, and IODP Expeditions 314/315/316 Scientific Party

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Introduction

Integrated Ocean Drilling Program (IODP) Expeditions 314, 315, and 316 were carried out as a unified program of drilling collectively known as Stage 1 of the Nankai Trough Seismogenic Zone Experiment, or NanTroSEIZE, the first multi-stage complex drilling project in IODP and the most ambitious effort in scientific ocean drilling to date (Tobin and Kinoshita, 2006b; Kinoshita et al., 2006). The first of four planned operational stages, the Stage 1 expeditions were conducted aboard the new riser-capable drilling vessel *Chikyu* from September 2007 to February 2008, and were *Chikyu*'s inaugural IODP expeditions. Seventy-one scientists from twelve countries took part in the three expeditions as shipboard participants, and thirty-three holes in total were drilled at eight sites, to as much as 1400 meters below the sea floor (Table 1, Fig. 1).

In the region offshore the Kii peninsula of Honshu, Japan, a transect of eight sites was drilled using riserless methods, targeting the accretionary complex in the frontal thrust region, the midslope mega-splay fault region, and the Kumano forearc basin region. Two of these sites were preparatory pilot holes for planned later deep-riser drilling operations, while the others targeted fault zone material at relatively shallow sub-bottom depth, where the faults were presumed to be aseismic. Expedition 314 was dedicated to *in situ* measurements of physical properties and borehole imaging through logging-while-drilling (LWD) in holes dedicated to that purpose. Expedition 315 was devoted to core sampling and downhole temperature measurements at one site in the mega-splay region and at another in the Kumano forearc basin. Expedition 316 targeted the frontal thrust fault and so-termed "mega-splay" (Tobin and Kinoshita, 2006a; Moore et al., 2007) fault region in the mid-slope environment. The initial scientific results on accretionary complex and fault zone structure, lithology and age, physical properties, and state of stress are summarized here and unified across the expeditions.

This article provides only an overview of the Stage 1 shipboard results; for the comprehensive results, please consult the IODP Expedition Report (Kinoshita et al., 2009) and the individual expedition summaries and site chapters therein.

Background and Objectives

The Nankai Trough subduction zone forearc is among the most intensively studied seismogenic and tsunamigenic plate boundary zones in the world, including previous DSDP and ODP drilling transects off Shikoku island southwest of the NanTroSEIZE study area. In the NanTroSEIZE transect, the offshore region exhibits a well-developed accretionary prism and forearc basin (Kumano basin), as well as a major thrust fault that splays from the deep plate interface at about 10 km depth beneath the Kumano basin and bisects the entire overriding prism, termed the "mega-splay" (Park et al., 2002; Moore et al., 2007). Similar mega-splay geometries are increasingly being identified in other subduction forearcs. The Nankai Trough in this region is considered a well-coupled megathrust (Wang and Hu, 2006) and exhibits

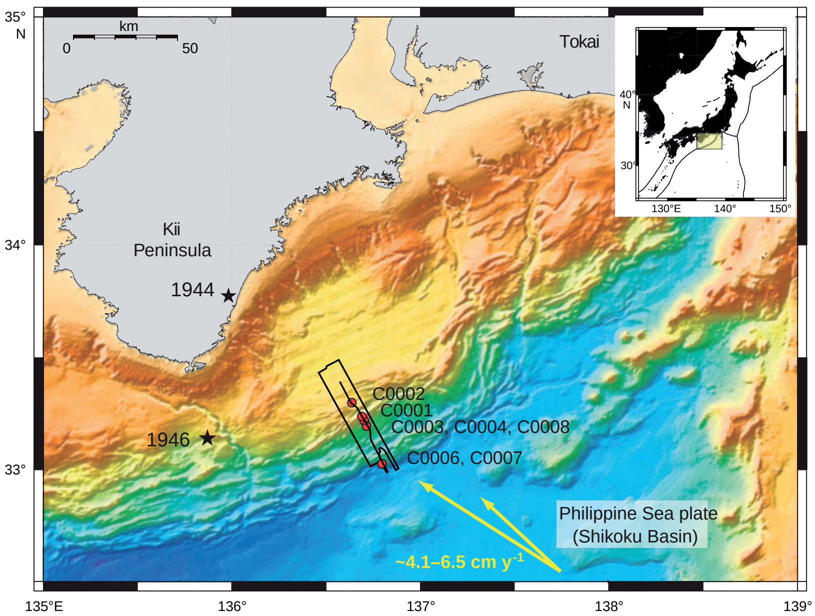

Figure 1. Location of sites drilled during the three expeditions of NanTroSEIZE Stage 1 (red circles) in the Nankai Trough off Kumano, Japan. Black box = location of the 2006 3-D seismic survey, black line = arbitrary line extracted from 3-D seismic volume (Fig. 3), yellow arrows = computed far-field convergence vectors between Philippine Sea plate and Japan (Seno et al., 1993; Heki, 2007). Stars = epicentral location of great earthquakes. Inset shows location of Nankai Trough.

no known interplate seismicity. The downgoing plate exhibited two ~M_w7 thrust and transpressional earthquakes in 2004 (Enescu et al., 2005), suggesting that, in contrast to many outer arc bending regions, this portion of the Nankai Trough's downgoing plate is in compression.

The NanTroSEIZE project is the first attempt to drill, sample, and instrument the seismogenic portion of a plate-boundary fault or megathrust within a subduction zone, identified as a very high priority in the IODP Initial Science Plan (2001). The fundamental goal of NanTroSEIZE science plan (Tobin and Kinoshita, 2006b) is to access, sample, and then instrument the faults in aseismic and seismogenic regions of the megathrust system. This involves drilling of key elements of the active plate boundary system at several locations off the Kii Peninsula, from the shallow onset of the plate interface to depths where earthquake slip and locking takes place (Figs. 1, 2). At this location, the plate interface and active mega-splay faults implicated in causing tsunami are accessible to drilling within the region of coseismic rupture in the 1944 Tonankai (magnitude 8.1) great earthquake (Baba et al., 2006). The final objective is to access and instrument the Nankai plate interface within the seismogenic zone through deep riser drilling, planned for a later stage in NanTroSEIZE.

The primary objectives of NanTroSEIZE Stage 1 were to complete the majority of the riserless coring and logging operations of the NanTroSEIZE transect as a whole—that is, all objectives besides the two planned deep riser-drilled sites into the plate boundary fault systems and the trench reference sites (see box; Tobin and Kinoshita, 2006a, 2006b).

NanTroSEIZE Stage 1 Riserless Drilling Expeditions: September 2007–February 2008

Scientific Targets

- The frontal thrust system at the toe of the accrtionary wedge
- The mid-wedge megasplay fault system
- 1000 m and 1400 m deep holes, respectively, at the two sites planned for later deep penetrations of the seismogenic zone faults

Expedition Breakdown of Drilling Activities

- Expedition 314: Logging-while-drilling (LWD) only transect of the all prism and forearc basin sites
- Expedition 315: Coring-focused drilling of the mega-splay fault thrust sheet and forearc basin
- Expedition 316: Coring-focused drilling of the shallow (<1000 mbsf) portions of the frontal thrust and mega-splay fault zone

Table 1. Drilling summary for Expeditions 314, 315, and 316 (pilot holes, including Site C0005 where no scientific drilling was done) and very short penetrations omitted).

Site & Hole	Expedition	Total Depth (mbsf)	Operations	Description
C0001D	314	976	LWD	Megasplay thrust sheet & riser pilot
C0001E	315	118	Core	
C0001F	315	249	Core	
C0001H	315	590	Core	
C0002A	314	1401	LWD	Kumano forearc basin and underlying prism
C0002B	315	1057	Core	
C0002D	315	204	Core	
C0003A	314	534	LWD	Megasplay thrust sheet
C0004B	314	400	Core	Megasplay fault zone
C0004C	316	135	Core	
C0004D	316	400	Core	
C0006B	314	885	LWD	Frontal thrust zone
C0006E	316	409	Core	
C0006F	316	603	Core	
C0007C	316	176	Core	Frontal thrust zone
C0007D	316	494	Core	
C0008A	316	358	Core	Slope deposits and prism
C0008C	316	176	Core	

Therefore *Chikyu* Expeditions 314–316 were planned to sample and characterize the sediments and relatively shallow levels of the major fault systems targeted for deep drilling in NanTroSEIZE to characterize fault properties outside the seismogenic zone, and to "pilot" the planned deep riser holes as a preparatory step towards borehole engineering for drilling to unprecedented depths (Tobin and Kinoshita, 2006a). As outlined below, we were successful in achieving a substantial majority of our objectives during Stage 1.

Stage 1 Expedition Strategy

NanTroSEIZE Stage 1 was divided into three individual expeditions, due to its five-month duration. The goals of Stage 1 were to obtain logs, cores, and downhole measurements through riserless drilling along the transect of sites (Tobin and Kinoshita, 2006a). Based on extensive past ODP experience of unsuccessful attempts to use wireline logging techniques in unstable accretionary prism environments, logging-while-drilling (LWD) was selected to obtain a comprehensive suite of logs; Expedition 314 was devoted entirely to LWD drilling of a first hole at each of the planned sites. Logging was performed using a state-of-the-art suite of LWD technology and included the measurement of natural gamma radiation, azimuthal gamma ray density, neutron porosity, full waveform sonic velocity, azimuthal resistivity imaging, zero-offset vertical seismic profile, ultrasonic caliper, and annular fluid pressure, though not all logs in this suite were collected at all sites (Kinoshita et al., 2009). The over-arching objective of the LWD program was to provide borehole data

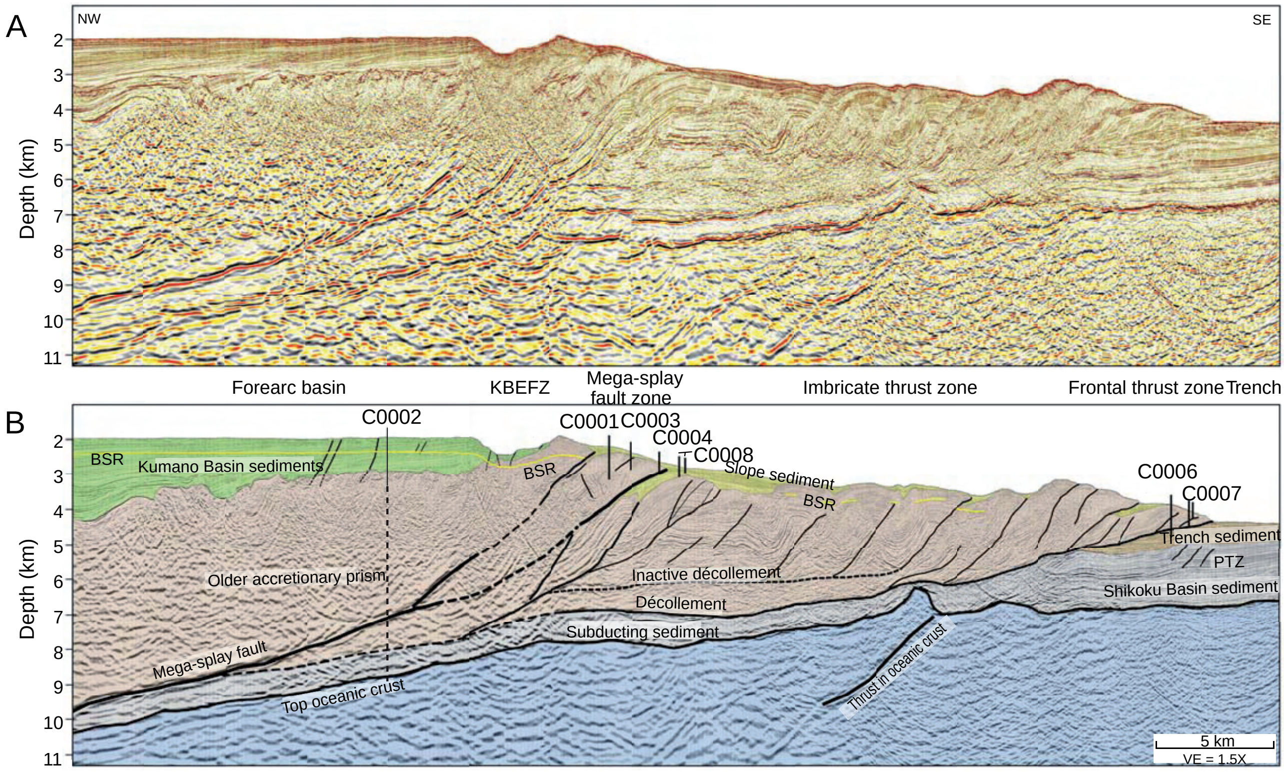

Figure 2. [A] Uninterpreted depth section, processed with pre-stack depth migration. [B] Interpreted version. Only a few representative faults are shown; dashed lines indicate less certain fault locations. Morpho-tectonic zones are shown between the two sections. Composite seismic line extracted from 3-D seismic volume, reproduced from Moore et al., (2009). The line crosses through (or near) all Stage 1 drill sites (solid vertical lines); location shown in Fig. 1. Location of planned Stage 3 ultra-deep drilling at Site C0002 is indicated by dashed vertical line. KBEFZ = Kumano Basin edge fault zone; PTZ = Protothrust zone; BSR=Bottom simulating reflection; VE = Vertical exaggeration.

to be used in conjunction with cores to document the geology, physical properties, mechanical state, fluid content, and stress conditions at the drilling site locations.

After Expedition 314 was completed, the same sites (for the most part) were revisited during Expeditions 315 and 316, in order to collect cores and other downhole measurements (e.g., temperature) in adjacent holes (typically 25–50 m away). Due to drilling challenges and other lost-time incidents causing contingency plans to be invoked a number of times, not all sites that were LWD logged were also cored, and vice versa. Multiple attempts to find sites to drill into the mega-splay and frontal thrust fault zones resulted in eight numbered sites drilled (note that at Site C0005, only pilot holes were drilled, and no scientific results were generated before this site was abandoned due to poor drilling conditions), with multiple holes at each one (Fig. 2, Table 1).

Site Descriptions and Results from Three Tectonic Domains

In this section, the principal results of drilling in each of the three tectonic regions are summarized, beginning with the two sites drilled in the frontal thrust region, moving to the four sites in the mid-slope, mega-splay fault zone region, and finally, the single Kumano basin site. This summary merges results from the Expedition 314 LWD logging drilling and the Exp. 315 or 316 coring and other measurements at each of these sites.

Frontal Thrust Region: Sites C0006 and C0007

Drilling at Sites C0006 (Expeditions 314 and 316) and C0007 (316 only) allowed examination of the frontal thrust region (Fig. 3). In Hole C0006B, LWD operations successfully drilled and logged to 885 meters below seafloor (mbsf), crossing the probable frontal thrust zone in the interval 657–711 mbsf (Expedition 314 Scientists, 2009a). The ambiguity exists because of the complex seismic reflectivity character, including apparent trench-fill channel deposit packages, and the lack of coring to this depth to elucidate the detailed structure. At 657 mbsf there is a zone of apparent high degree of fracturing/brecciation (based on LWD resistivity images) that is the most likely candidate for the frontal thrust. On Expedition 316, however, Holes C0006E and C0006F did not penetrate to this depth before drilling and coring was stopped because of poor borehole conditions and extremely poor core recovery. Several fault zones within the prism (above the frontal thrust) were penetrated and recovered, identified by concentrations of core-scale structural features, biostratigraphically-identified inversions of sediment age, and correlation with seismic reflection

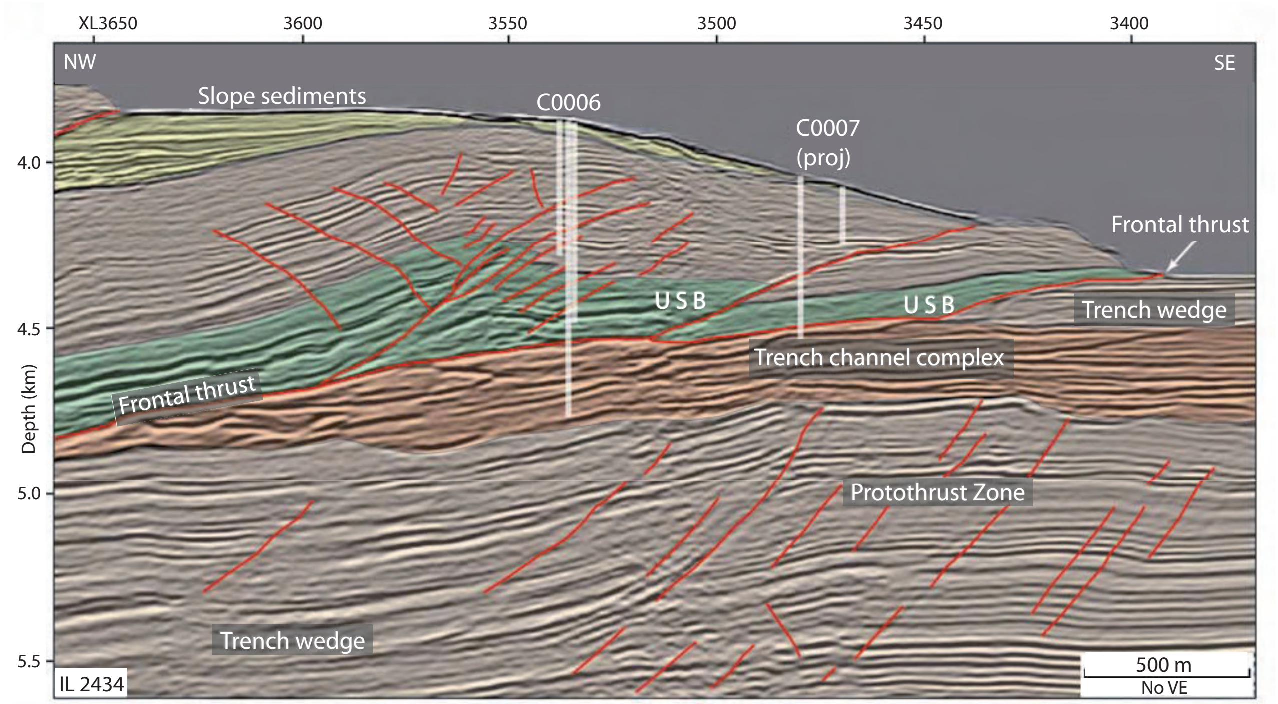

Figure 3. Inline seismic section for the frontal thrust region, Sites C0006 and C0007. Reproduced from Moore et al. (2009).

imaging (Expedition 316 Scientists, 2009a). LWD gamma and resistivity logs in Hole C0006B indicate that the interval beneath 711 mbsf is dominated by massive sand, consistent with a position below the frontal thrust in the trench fill deposits, correlative to the footwall cored at Site C0007 (see next paragraph).

The plate boundary frontal thrust was successfully cored at Site C0007 nearby (Figs. 4, 5), and thrust fault material ranging from breccia to fault gouge was recovered (Expedition 316 Scientists, 2009b). The lowermost part of Fault Zone 3 at 438 m core-based depth below seafloor (CSF) is intensely brecciated into fragments ~1–10 mm in size (Fig. 5). This 29-cm-thick breccia shows a foliated aspect with an anastomosing network of polished and striated surfaces. At the base of this zone, a dark 2-mm-thick layer sharply separates intensely brecciated hemipelagic mudstone above from unbroken hemipelagic mudstone and ash below. There is a biostratigraphic age reversal as well. These features indicate that the thin dark layer most likely represents extreme localization of slip associated with thrust faulting. This frontal thrust zone at 418–438 m CSF is located in a stratigraphic package of late Miocene mud, which appears to be similar to the Shikoku Basin facies that hosts the décollement in the Muroto and Ashizuri transects (Moore et al., 2001). The footwall proved to be remarkably coarse-grained, as it was dominated by sand and gravel trench-axial channel facies deposits, and core recovery was very poor in this interval.

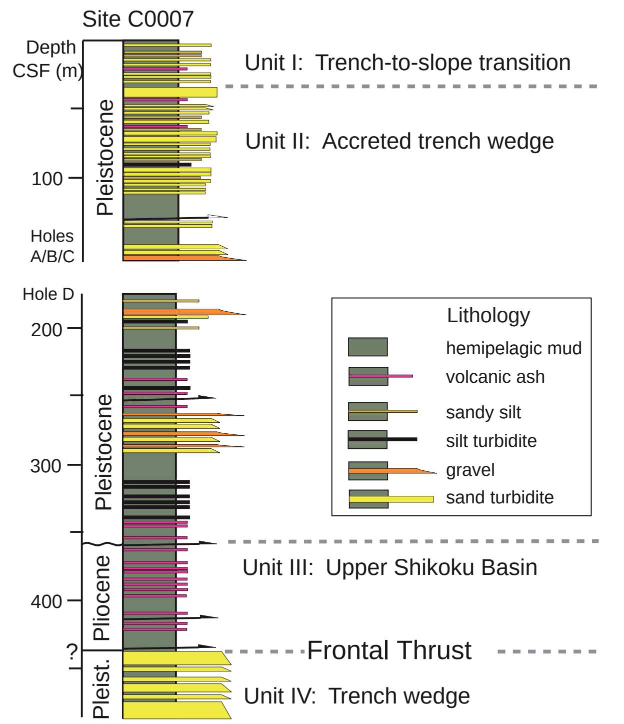

Figure 4. Hole C0007D summary of coring, lithology, and major faults.

Lithologic Unit I sediments at Site C0006 (Fig. 3) are interpreted as representing a transition from trench to slope deposition, while Unit II is composed of trench fill facies sediment; thus, the Unit I/II boundary records the uplift of trench material into the prism. Unit I sediments are younger than or the same age as sediments filling the basin behind the thrust. The age of this transition is 0.78–0.44 Ma. Seismic data show that about 6 km of overriding of trench channel facies by the frontal thrust has taken place since this fault initiation time (Fig. 3; Moore et al., 2009) without development of any further frontal accretion thrusts. How such a large amount of slip has concentrated within the fault zone and how the evolution of the fault zone has affected the characteristic features in this region are two important issues for post-expedition research. Furthermore, taking into account the relative plate motion velocity of ~4 cm yr^{-1} between the overriding Japanese islands and the Philippine Sea plate (Seno et al., 1993), we determine the relative total slip distance has to be ~40 km, not 6 km. Therefore, the majority of the total shortening must be taken up elsewhere within the accretionary prism.

The accretionary prism in the frontal thrust region is deformed by thrusting, as visible on the seismic profiles (Figs. 2, 3; Moore et al., 2009). Most of the thrusts inferred from the seismic profiles and LWD data were confirmed through age reversals, fault zones sampled in cores, and repetition of specific strata, but some additional faults were also defined during Expedition 316 drilling. Initial chemical analyses of interstitial fluid (porewater geochemistry) and microbial habitat around most of these "intraprism" thrusts do not indicate any signal of active fluid flow focused along these faults or in other permeable conduits.

In contrast to such intraprism thrusts, many normal faults are developed at the core scale and appear to be the youngest deformation feature. Clear slope-parallel mass sliding is observed from the submarine topography, seismic profiles, and shallow cores (Fig. 3). These facts suggest that the taper angle of the prism locally at the toe is presently above the critical wedge taper angle and is unstable. There is evidence that the system is currently in a period of wedge collapse, perhaps as a readjustment to the passage of subducted basement topography.

Porosity data suggest that a considerable thickness of material has been eroded or otherwise removed from the surface at Sites C0006 and C0007. Porosity is quite low at shallow depths below the surface, reaching 48% at 5 m and 34 m CSF at Sites C0006 and C0007, respectively. In contrast, porosity does not decrease to <50% until ~150 to ~200 mbsf, at other sites on the Stage 1 transect farther landward in the prism.

Mega-Splay Fault Region (Sites C0001, C0003, C0004, and C0008)

The out-of-sequence mega-splay fault zone branches into a number of individual splays as it enters the upper few kilometers of the subsurface (Fig. 2; Moore et al., 2009). A series of sites targeted the thrust sheet, fault zone, and footwall of the lower of these branches, which was judged to be the most active and most significant of the seismically imaged splays (Tobin and Kinoshita, 2006b; Moore et al., 2009).

*Site C0001***:** Site C0001 was chronologically first in drilling, and targeted only the thrust sheet (not the underlying fault itself) in the most landward position (the fault zone was judged too deep at ~2000 mbsf to access with riserless drilling at this site). For NanTroSEIZE Stage 2, 3.5-km riser drilling had been planned at Site C0001, located at a small bench on the hanging wall of the main branch of the mega-splay fault (Fig. 6) where a small slope basin with coherent layered reflectors is developed, overlying a more seismically-chaotic thrust sheet above the splay fault. In Stage 1, pilot-scale drilling of the uppermost ~1000 mbsf at this site was executed to test conditions for riser drilling and to set the surface casing for this later effort. The results of this pilot, detailed below, indicate that this may be a difficult location for a riser site, and that plan is being reevaluated.

We first drilled an LWD-only hole at this site (Expedition 314 Scientists, 2009b), achieving 976 m of penetration (just 24 m short of the planned depth, but sufficient to achieve all logging objectives). Difficult hole conditions were encountered, including an interval of high drill string torque due to apparent borehole caving, enlargement, and partial collapse around 460–540 mbsf, an interval that became known as "the sticky zone". Logging results suggested that the sediments of the hanging wall thrust sheet are primarily muds and mudstones with some silty to sandy (or ash-bearing) sediments, overlain by ~200 m of hemipelagic slope deposits. Resistivity imaging suggested widespread fracturing and variable bedding orientation,

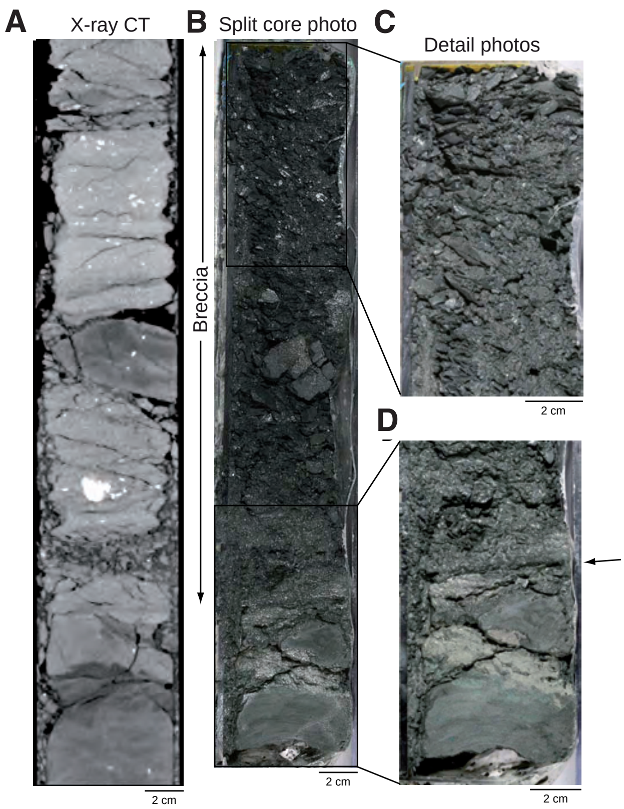

Figure 5. Fault core example from the frontal thrust region at Site C0007 (Expedition 316). Appearance of concentrated deformation in lower portion of frontal thrust fault Zone 3, at a depth of 438 mbsf. [A] CT image and [B] core photograph of finely brecciated hemipelagic mudstone (interval 316-C0007D-29R-2, 37–73 cm). [C] Close-up of finely brecciated interval. [D] Thin (2-mm-thick) dark layer (arrow) developed at base of finely brecciated interval..

indicative of strong deformation, especially below ~460 mbsf.

Subsequent coring at this site during Expedition 315 confirmed and greatly added to these observations (Fig. 6B). Results of the coring document the age and make-up of the deformed mega-splay thrust sheet and overlying slope apron deposits, as well as structural features and inferences on evolution of the stress state (Expedition 315 Scientists, 2009a). Despite numerous attempts in multiple holes at this site, the challenges posed by "the sticky zone" proved too great to advance the coring beyond 458 mbsf. The cored interval includes the slope basin (Unit I) and the top ~250 m of the underlying accretionary prism (Unit II). Unit I is composed mainly of Quaternary to late Pliocene silty clay and clayey silt with volcanic ash, while Unit II is made up of older (late-Pliocene to Miocene) mud-dominated sediments. The boundary between Units I and II, identified at 207 mbsf, is an unconformity located immediately below a thick sand layer. Unit II exhibits much more deformation at core and seismic scales, and a range of small-scale structures including normal, thrust, and strike-slip faults. Kinematic solutions computed from normal and thrust faults are consistent with northeast-southwest extension and northwest-southeast shortening, respectively, suggesting that tectonic shortening during emplacement of the thrust sheet and contemporaneous or later extension perpendicular to that are recorded. The extension may be evidence of near-surface collapse of the slope.

We found it interesting to note that at the frontal thrust area, interstitial water geochemistry and organic geochemistry data do not show clear evidence for advection of chemically-distinct fluids from depth.

*Site C0003***:** This proposed site was intended to begin the downdip transect of the mega-splay fault system by sampling a relatively shallow, presumably aseismogenic, point on the fault zone at ~800 mbsf (Fig. 7). Unfortunately, we encountered very difficult drilling conditions at this site, such as especially pronounced caving and

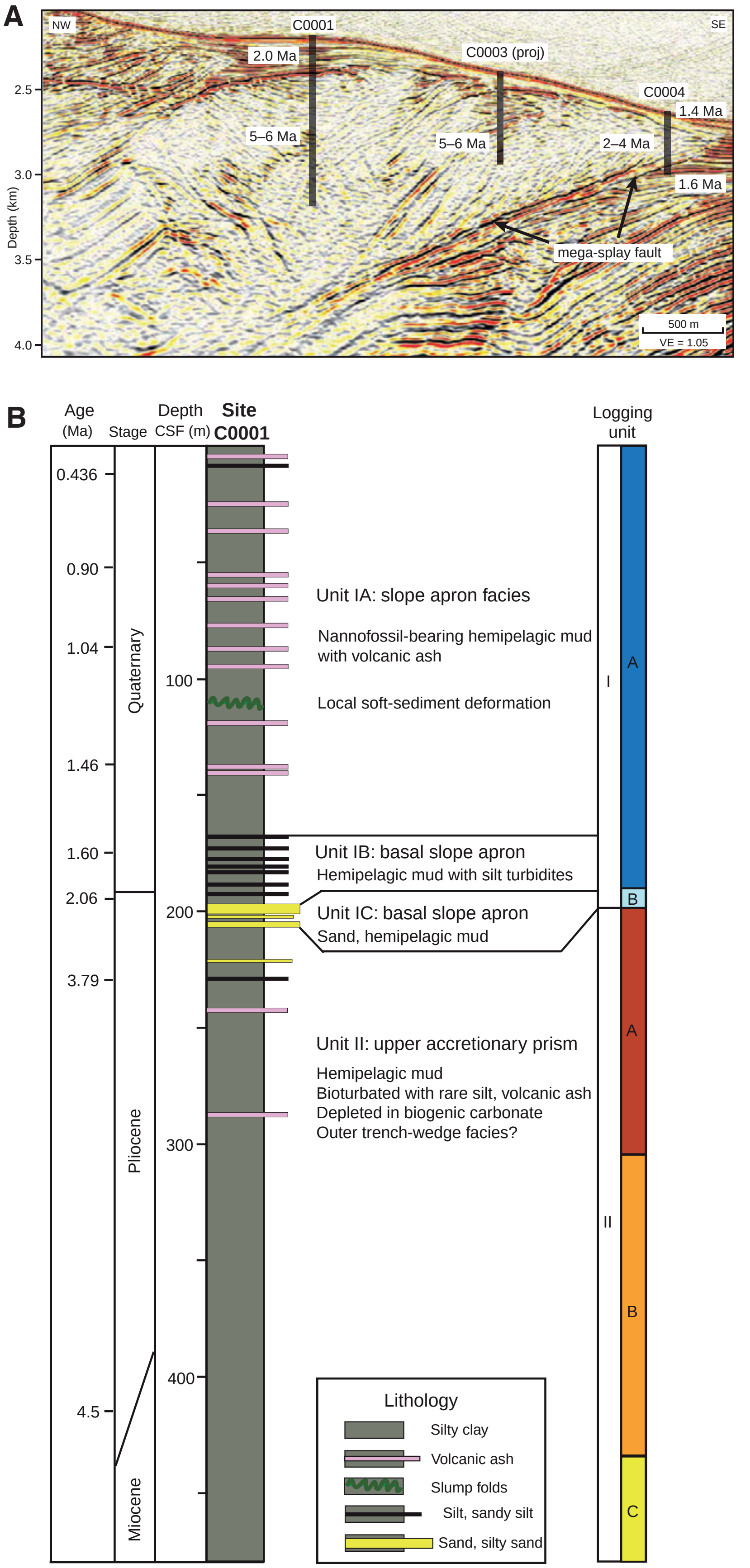

Figure 6. [A] Inline PSDM seismic section through the mega-splay fault thrust sheet sites, showing total drilled depth at each site. Age labels show maximum sediment depositional ages based on nannofossil biostratigraphy. [B] Site C0001 summary column of lithostratigraphy, logging units, and age of sediments determined through biostratigraphy and paleomagnetic data.

washout of likely fault zones and possibly sandy intervals, which caused the drill string to become irretrievably stuck before reaching the primary objective (Expedition 314 Scientists, 2009c). While drillers worked to free the stuck pipe, it parted and we were ultimately unable to recover the bottom hole assembly with the LWD tool string and ~200 m of drill collars at this site. Nevertheless, real-time data transmission provided substantial logging data from the seafloor to ~530 m LWD depth below seafloor (LSF). No further drilling or coring was attempted here; we instead moved to Site C0004 (see next section).

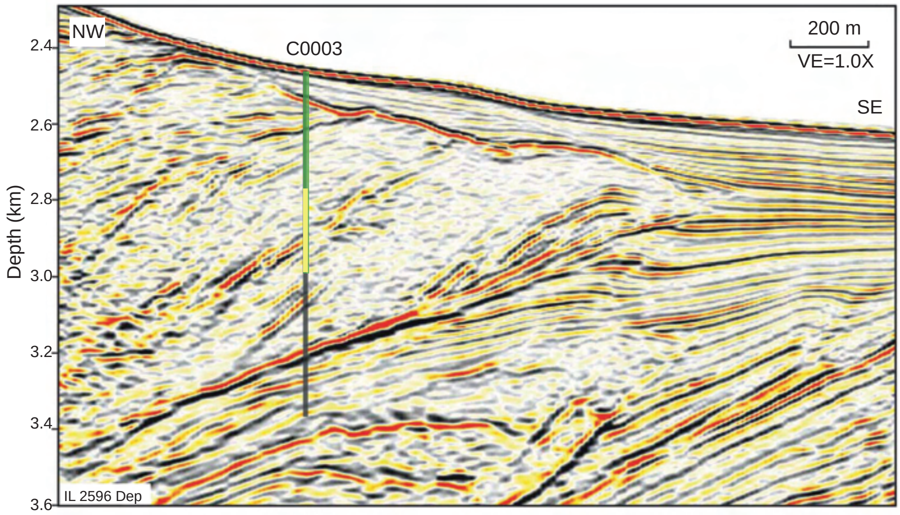

Figure 7. Site C0003 on Inline 2596. Black line is the originally planned total depth of 1000 mbsf; green line is actual depth achieved when the drill string became stuck. Yellow line is approximate length of stuck and abandoned bottom-hole assembly . The reflector that intersects the borehole at ~2.9 km depth is interpreted as a fault zone, and is the probable source of dated cavings in the hole.

Consistent with the other midslope sites, the lithology at C0003 is apparently composed of relatively coarse silt-sand and hemipelagic mud in the shallowest portion, underlain by more clay-rich, generally homogeneous muddy deposits interrupted by prominent zones of washouts interpreted as brecciated intervals, indicating likely faults (Expedition 314 Scientists, 2009c). The seismic reflection imaging shows that this site was drilled into a series of at least three individual thrust sheets within the hanging wall of the mega-splay fault system (Fig. 7). Therefore, major washout zones identified in logs at ~240 m and 420–450 m LSF are likely to be strongly brecciated damage zones from subsidiary thrusts, analogous to fault breccia recovered in core at other sites.

The seismic interpretation is consistent with substantial uplift of the thrust sheet bringing older and more deeply buried accretionary prism rocks to within 500 m of the seafloor. Log density data show relatively constant and high values for this depth; these suggest that anomalously well-indurated rocks make up the thrust sheet. When the broken section of drill pipe was recovered to the rig floor after loss of the LWD string, it was plugged with numerous large chunks (up to 5–8 cm in diameter) of cavings that had come from an unknown position in the hole. This material had a nannofossil age of late Miocene (5.5–7.2 Ma), bulk density of 2.1 g cm^{-3}, and P-wave velocity of ~2.1 km s^{-1}, also consistent with the thrust sheet rocks having been uplifted from greater depth within the accretionary complex.

*Site C0004***:** Site C0004 is located seaward of Sites C0001 and C0003 (Fig. 6). It targeted the prominent splay fault reflector at a depth of approximately 300 mbsf. The overlying thrust sheet, the mega-splay fault zone, and ~100 m of the footwall sediments were successfully drilled with LWD logging (Expedition 314) and coring (Expedition 316). Drilling at this site also examined the youngest sediments on the slope overlying the accretionary prism, which consist of slowly deposited hemipelagic marine sediments and redeposited material from upslope. This redeposited material provides information about past slope failures, which may be related to past mega-splay movement, earthquakes, and tsunamigenesis. This will be the subject of future work on the core samples. The top of the prism corresponds to a prominent unconformity (age gap = ~1My) that displays pyrite and other mineralization. Structural observations of core material from the fault zone and two age reversals suggested by nannofossils indicate a complex history of deformation. Sediments under the fault zone were sampled to understand their deformation, consolidation, and fluid flow history. Further results and discussion of Site C0004 are summarized below in the “Key Results” section.

*Site C0008***:** Drilling at Site C0008 targeted the slope basin seaward of the mega-splay fault (Fig. 2B) as a complement to Site C0004, which is about 1 km farther landward. This basin records the history of fault movement. Sediments are Pleistocene to late Pliocene hemipelagic silts and clays with ashes (Expedition 316 Scientists, 2009c). Several gravelly sequences were identified and interpreted as indicative of mass transport complexes. Sediments of the slope basin at Site C0008 provide a “reference site” for the sediments underthrust beneath the mega-splay fault. Comparison of the interval 190–200 m CSF in Hole C0008A (with an average porosity of 50%) and the correlated interval 320–330 m CSF in the mega-splay footwall section of Hole C0004D (average porosity of 43%) suggests the sediments are dewatering during underthrusting. Evidence for lateral flow from the C0004 area toward Site C0008 is provided by C1/C2 (methane/ethane; one indicator of biogenic vs. thermogenic gas origin) ratios that are slightly lower than expected for biogenic production at the estimated *in situ* temperature, but they are similar to those at Site C0004. Lateral flow along sand layers could transmit fluids from areas of higher temperature because of greater burial beneath the splay fault, driving fluids out along permeable sandy layers.

Kumano Forearc Basin Region: Site C0002

Site C0002 sampled the Kumano forearc basin and the underlying old accretionary prism material (Figs. 2, 8). LWD drilling during Expedition 314 was very successful here, with a single hole achieving 1401 m penetration—the deepest LWD hole in scientific ocean drilling to date—and we show a comprehensive log summary in Figure 8A (Expedition 314 Scientists, 2009d). Approximately 940 m of this drilling was through the sediments of the Kumano forearc basin, whereas the lower ~460 m accessed the underlying rocks interpreted to be the accretionary prism formed through earlier frontal accretion.

This site is slated to be the centerpiece of the NanTroSEIZE project, with six or more kilometers of drilling planned to access the plate boundary at seismogenic zone depths in a later stage (Fig. 2). Therefore, understanding the physical properties and documenting tectonic processes and lithology in the hanging wall of the plate boundary here were important goals of Stage 1 drilling, not the least because of the need for high-quality borehole engineering parameters to plan riser drilling. Scientifically, the hole records the timing and history of the mega-splay system in the formation and filling of the Kumano basin, and it was used to document the present-day stress regime in this portion of the margin (see "Summary of Key Results" below).

During Expedition 315, Site C0002 was drilled again (in two separate holes) to 1057 m CSF, with coring of the intervals 0–204 m CSF and 475–1057 m CSF (Fig. 8B, 8C). The Kumano Basin is a young feature (mostly Quaternary) with a high sedimentation rate (>800 m Ma^{-1}) overlying a late Miocene (5–6 Ma) accretionary prism. This is much younger than most of the Tertiary Shimanto belt outcropping onland. Biostratigraphic data show that the transition from Pliocene to late Miocene strata occurs as a marked age gap around 922 m CSF.

We cored across the basal unconformity of this Kumano forearc basin at ~922 m CSF and another 135 m into the accretionary prism (Expedition 315 Scientists, 2009b). The forearc basin sequence was divided into two units based on lithofacies. All units are dominated by mud and mudstone; however, Units I and II contain more sand and silt intercalation and have a much faster sedimentation rate than the basal deposits of Unit III. Underlying accretionary prism materials contain moderately more lithified—and much more deformed—sediments.

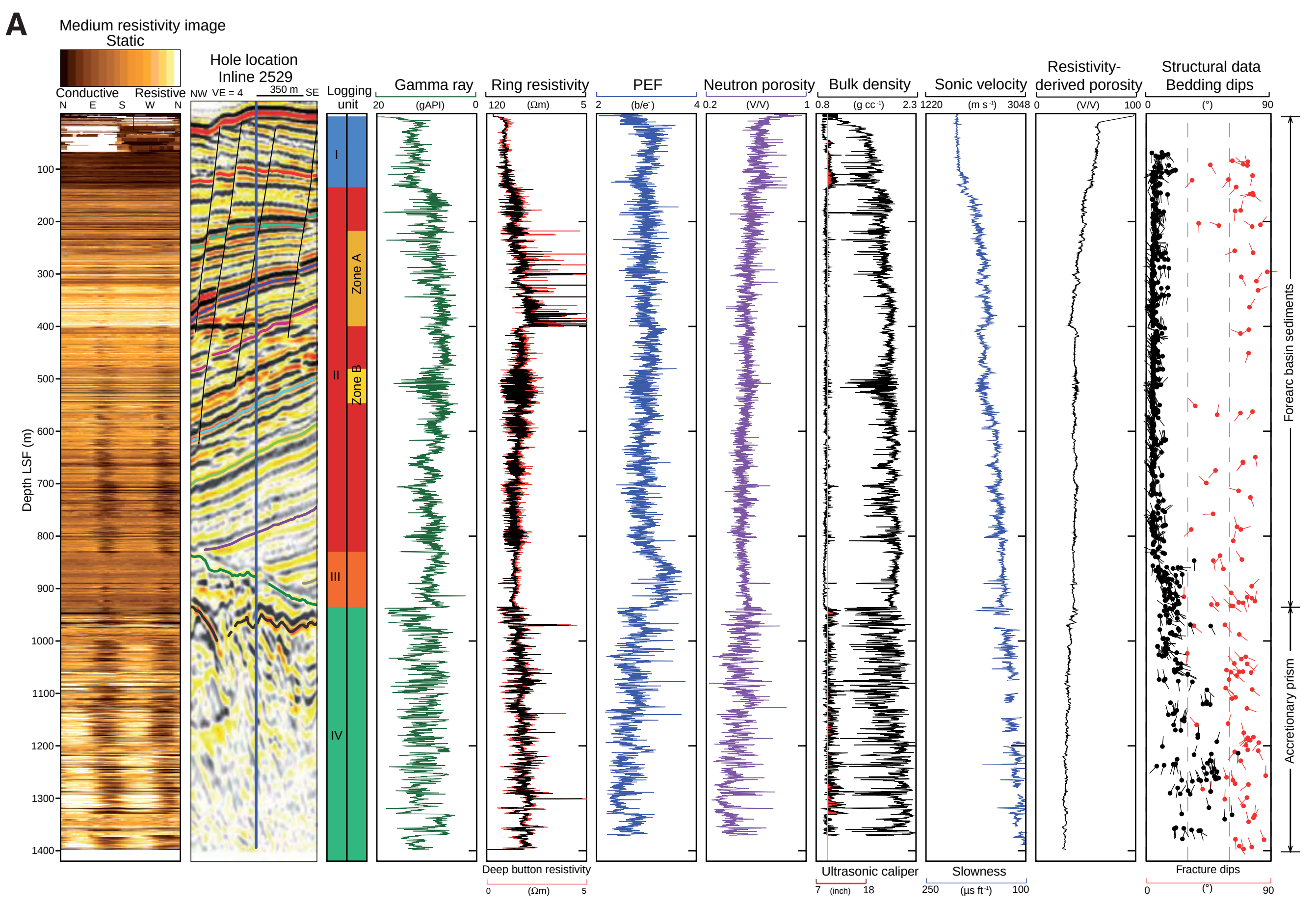

Figure 8 [A]. Site C0002 Results – Summary plots of major LWD logs for the full 1400-m interval drilled. (Figure 8. [B] shown on p.12 and [C] shown on p.13)

At Site C0002, a well-developed bottom simulating reflector (BSR) is imaged in the seismic data, and LWD logs recorded comprehensive *in situ* information about the nature of this gas hydrate BSR (Expedition 314 Scientists, 2009d). Resistivity logs showed a pattern of elevated resistivity background and spikes for ~200 m above the BSR depth at ~400 m LSF (Fig. 8). The gamma response indicated that the spikes are in especially sandy intervals as thick as 1–2 m, which were interpreted as the coarse basal beds in turbidite deposits. Sonic and resistivity responses are consistent with pore space in these sands being partially filled and "cemented" with gas hydrate. In contrast, similar sands below the BSR reflector depth show no elevated resistivity response. In a zone 80 m deeper and ~70 m thick, a low resistivity response in the sandy beds suggests a potential gas-charged interval beneath the gas hydrate stability field. The logging data indicate that the BSR reflectivity is a response to a small velocity high from hydrate cement in the hydrate stability zone and to a more significant velocity low caused by the presence of uncemented sediments and/or free gas below the stability field.

Ongoing log analysis integrated with 3-D seismic analysis will quantify the amount of pore space charged with hydrate in the zone above the BSR and the total amount of gas in this region of the Kumano Basin section. During Expedition 316, Site C0002 was cored late in the expedition as a contingency operation. The BSR interval and overlying apparent gas hydrate-rich zone was not cored in order to allow time for deeper objectives..

Summary of Key Results

Lithology, Structure, and Recent Activity of Mega-Splay Fault and Associated Thrust Sheet (Sites C0001, C0004, and C0008):

A key question for the NanTroSEIZE transect is whether or not the mega-splay style of fault development indicates that tsunamigenic coseismic slip comes near to the surface preferentially in the mid-slope region, as opposed to extending along the basal décollement out toward the trench. Based on seismic and tsunami inversion studies combined with seismic reflection research, various workers have suggested that the splay fault system in this area slipped during the 1944 Tonankai M_w 8.2 earthquake to generate the observed tsunami (Baba et al., 2006; Park et al., 2002). From a 3-D seismic reflection investigation, Moore et al. (2007) also suggest recent historical and geological accumulation of displacement along the mid-slope mega-splay fault. The age reversal from Pliocene to Pleistocene documented beneath the splay fault during Expedition 316 (Fig. 6) is consistent with geologically recent activity. However, age resolution is, of course, insufficient to document historical fault activity.

Integration of seismic imaging, coring, and logging results for Site C0004 provides evidence for recent activity of the splay fault. The splay fault clearly thrusts the hanging wall prism over younger slope sediments in the footwall; however, the youngest (less than about 1 Ma) slope sediments that cover the fault appear not to be cut by the fault. In addition, the lack of a slope break on the seafloor above the fault might also suggest that this splay fault is presently not active but ceased activity in the

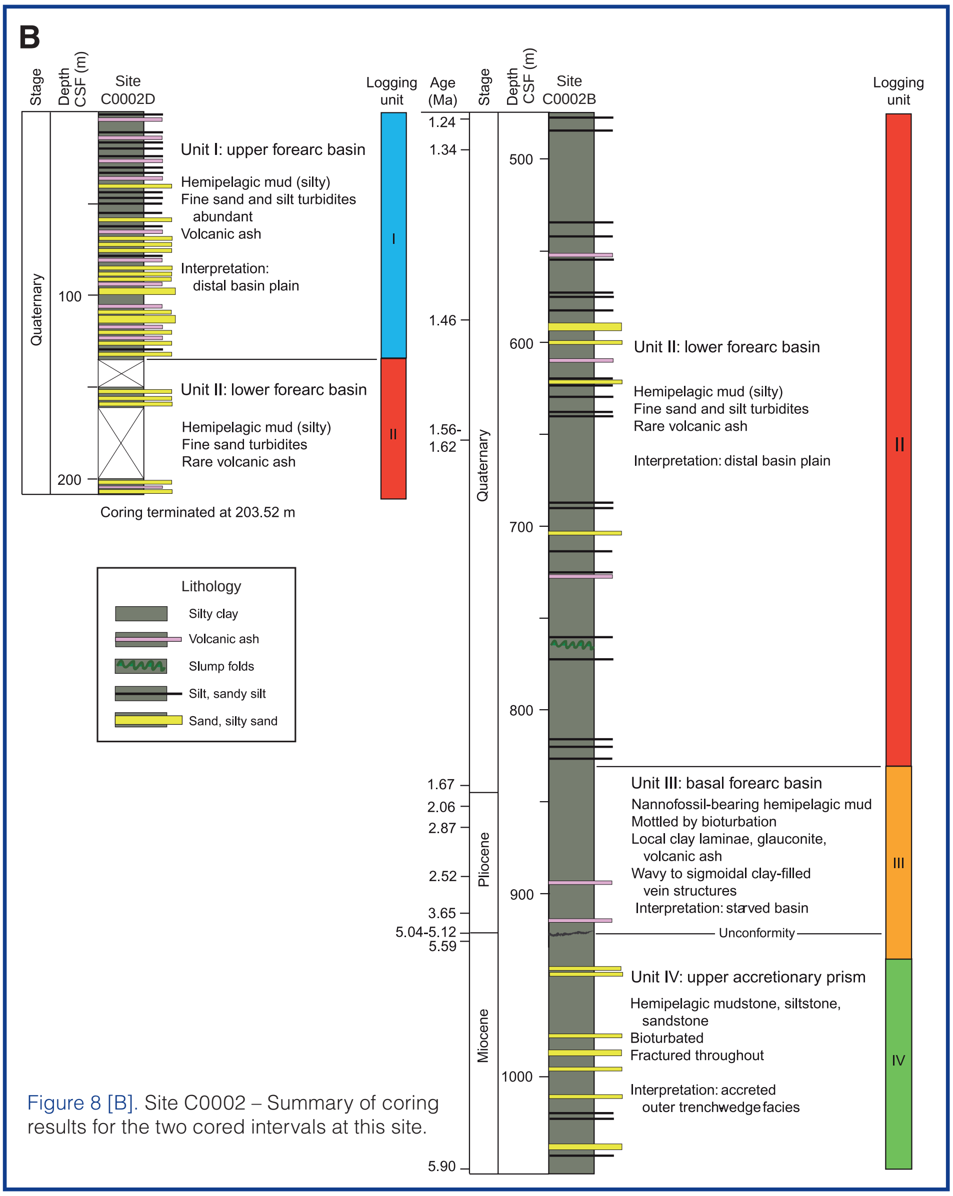

Figure 8 [B]. Site C0002 – Summary of coring results for the two cored intervals at this site.

recent past. However, the following shipboard results interpreted in the context of seismic reflection imaging provide support for the alternate interpretation that the splay fault is active as a blind thrust, in which the tip of the fault has not propagated to the surface but remains buried. Shallow cover sediments were found in cores to be composed of repeated mass transport complexes associated with repeated slope collapses and rip-up debris generation. Pleistocene cover sediments dip steeply approximately parallel to the slope and are cut by numerous normal faults, expressed at core and seismic scales (Expedition 316 scientists, 2009d). Slip on deeper levels of the fault zone could be manifested in some combination of folding and layer-parallel slip in the shallow slope sediments draping the uppermost portion of the mega-splay, as well as the possible triggering of numerous marine slump or slide deposits.

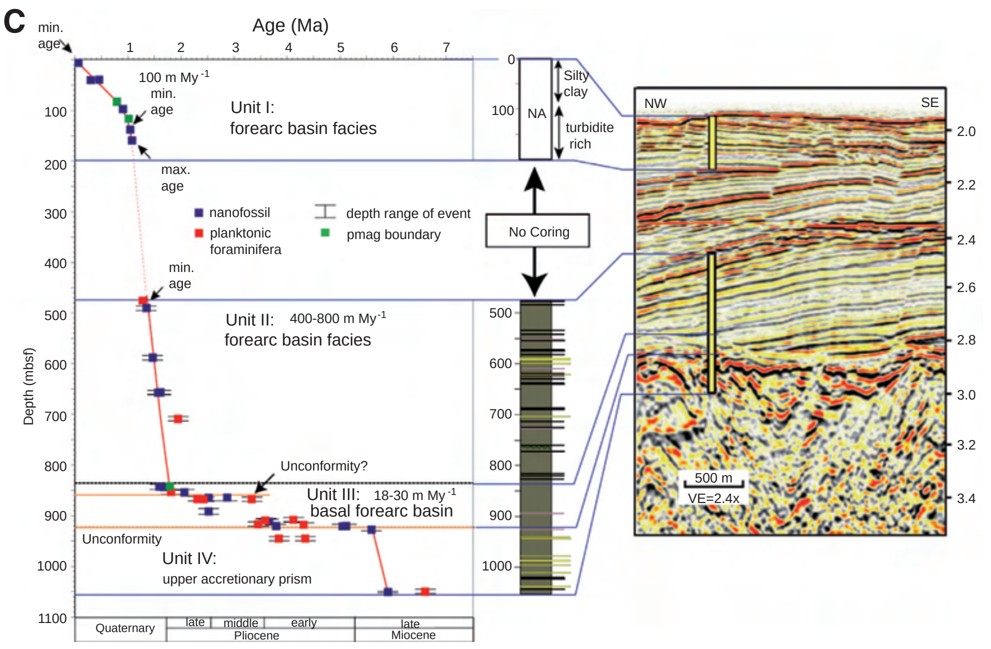

Figure 8 [C]. Site C0002 – Biostratigraphic age determinations for the cored intervals, illustrating contrast between prism, slope drape, and forearc basin sediment accumulation timing and rates.

Despite inferences of recent activity on the splay fault system, no porosity inversion is observed beneath the splay fault; this contrasts with previous results from the décollement of the Muroto transect (Screaton et al., 2002), in which a clear porosity inversion across the fault likely reflects fluid overpressure. Unlike the Muroto transect décollement, the splay fault system observed at Site C0004 has permeable pathways for dewatering provided by the observed sand and coarse ash layers.

Age of Cover Sequence and Uplifted Accretionary Prism Units

Rocks of the thrust sheet below 500 m LSF at Site C0001 and also of the cavings sampled at Site C0003 are anomalously dense relative to their present depth of burial, with high sonic/seismic velocity, indicating relatively advanced lithification. This suggests significant uplift and exhumation along the splay thrust. These inferences are consistent with the age determinations made on cores, showing that this thrust sheet contains rocks several millions of years old, in contrast to the immediately overlying Pleistocene and younger slope deposits (Fig. 6). Thrust sheet material drilled at C0004 is substantially younger than the analogous material at C0001 or C0003, suggesting that the mega-splay thrust sheet contains internal structural imbrication and has incorporated material progressively as it advanced.

At all of the sites landward of the frontal thrust area, units interpreted to be an uplifted section that was frontally accreted to the prism are covered by varying amounts of slope drape. In the case of Site C0002, this slope drape is in turn covered with the thick, dominantly Pleistocene Kumano forearc basin section (Fig. 2). Biostratigraphy (predominantly by nannofossil zones) and magnetostratigraphy define the ages of sediments above and below these boundaries, which also record time gaps of various durations between the prism section and cover (Figs. 6, 8C).

In the frontal thrust region at Site C0006, the transition from uplifted trench sediments into the overlying slope apron cover sediments is dated to 0.436–0.78 Ma, which presumably records the timing of initial frontal thrust activity. Only twenty-seven meters of younger slope cover overlies this boundary, and this implies potential removal of young deposits through slumping or mass wasting.

Moving to the mid-slope mega-splay fault region, the oldest sediment at the base of the slope cover at Site C0004 (dated at 1.46 Ma) rests on sediments that are 1.1. My older than that. Just a short distance landward at Site C0001, in the same apparent overall thrust complex (Figs. 2, 6), the age of the base of the slope apron is 2.0 Ma—substantially older than C0004—resting on a nearly 4 Ma accreted section. Ten kilometers further landward in the Kumano basin at Site C0002, the slope apron lies on top of the accreted complex at a depositional age of 3.79 Ma and rests on >5 Ma sediments in the accreted section. This landward progression of successively older dates marking the uplift and surface exposure of Shikoku basin sediments is consistent with progressive growth of the accretionary prism through late Miocene to Quaternary time.

Furthermore, the slope apron at Site C0002 accumulated very slowly until ~1.5 Ma, then more than 800 meters of forearc basin turbidites accumulated rapidly (Fig. 8C). The implication is that the onset of splay fault uplift of a pronounced outer arc high and/or capture of a significant turbidite sediment source for the basin was abrupt in the early Pleistocene.

Indicators of Stress Regime

Borehole breakouts and present-day stress orientations: Borehole breakouts were observed at all four sites for which we have imaging data. They also show very systematic orientations (Fig. 9). In a vertical borehole, the orientation of breakouts, or compressive borehole wall failures upon drilling, is a well-established indicator of the orientation of the horizontal maximum principal stress in the present-day stress field (Zoback et al., 2003). Drilling-induced tensile fractures (DITF) were observed less frequently, primarily at Site C0001 in the splay fault thrust sheet. Breakout orientations at Sites C0001, C0004, and C0006 all indicate northwest–southeast azimuths of the maximum horizontal principal stress (SH_{max}) (Fig. 10). In the thrust-dominated tectonic environment, this is consistent with trench-normal shortening, although strike-slip and/or normal faulting stress states are also permissible (see next section). By contrast, at Site C0002 in the Kumano Basin, the orientation of SH_{max} is northeast–southwest at 134°, or very nearly perpendicular to that in the more trenchward sites (Figs. 9, 10). This is consistent with a normal faulting stress state that extends through the basin section (which, in fact, exhibits numerous normal faults) and also in the upper 400 m (at least) of the underlying older accretionary prism section; however, given that stress magnitudes are unknown, the breakout orientation here also does not preclude strike-slip or reverse faulting stress state. This contrast between the outer accretionary prism and the forearc basin region (including the buried prism rocks beneath) suggests that the tectonic stress orientations differ markedly in the upper part of the prism at sites just a few kilometers apart along our transect. Implications of these data will be explored in post-expedition research to understand the mechanical state of the prism and basins.

Paleostress from core-based structural data: Core-scale structures can be used to infer paleostress regimes, while breakouts respond to present-day stress. Oriented structural data from cores drilled on Expedition 315 in Holes C0002C and C0002D (Kumano Basin site) show small-scale structures consistent with the interpretation that the present-day stress field is extensional and directed NE-SW. This agrees very well with the interpretation of breakout data for the present-day stress field (Expedition 315 Scientists, 2009b).

In the minor structures observed in the mega-splay thrust sheet at C0001 and at the frontal thrust at C0006, reverse and normal faults were documented (with minor strike-slip as well). In general, there is an overall indication at both of these sites that the youngest and/or most numerous small faults are normal and record extensional conditions striking NW-SE and dipping sub-equally to NE and SW (Expedition 315 Scientists, 2009a; Expedition 316 Scientists, 2009a). In the case of Site C0006, this was interpreted by the ship-board party as evidence of geologically recent collapse of an oversteepened frontal wedge (Expedition 316 Scientists, 2009a). By contrast, at Site C0004, normal faults were not prominent in the front of the mega-splay thrust sheet (except in a thin and shallow slope cover sequence of 0–78 mbsf), and reverse faults dominate, though they were not numerous and generally were not in oriented intervals of the core.

Site C0001, on the other hand, shows reverse faulting beneath the slope cover but overprinted by normal faults recording NE-SW directed extension, even in the thrust sheet, similar to C0006 at the frontal thrust area, and

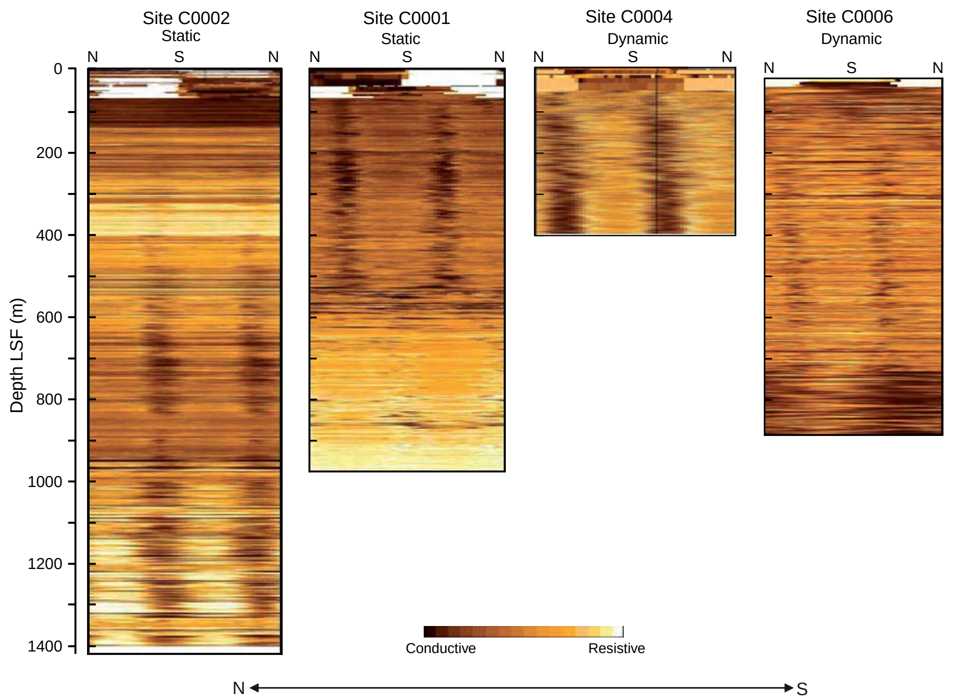

Figure 9. Resistivity at bit images synoptically showing full depth extent of LWD logged intervals at Sites C0001, C0002, C0004, and C0006. Vertical paired dark bands are images of borehole breakouts that have been interpreted in order to generate the average SH_{max} azimuths shown in Figure 10.

approximately orthogonal to the present-day SH_{max} direction. These apparently heterogeneous paleostress states at the various sites along the lower-slope portion of the transect (i.e., all except for C0002) may not be in conflict if the three principal stresses differ only modestly at these shallow depths, and small changes in their relative magnitude can effect a “flip” in stress/faulting regime. As the wedge develops, shortens, rides over basement topography, it might respond by successive and frequent flips in faulting regime, especially in the upper 1000 meters or so. The remarkably uniform orientation of the breakouts down each hole would typically be interpreted as evidence of a high-differential stress, homogeneous stress state environment. Further analysis of the stress conditions and this apparent paradox awaits post-cruise efforts.

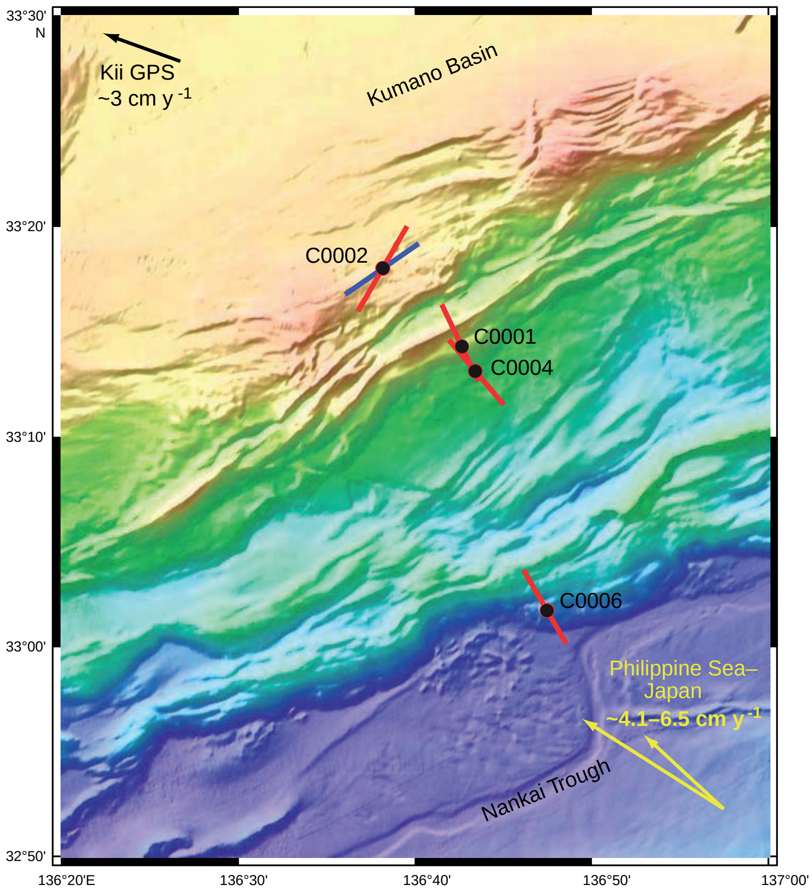

Figure 10. Azimuth of maximum horizontal stress estimated from borehole breakout images at Sites C0001, C0002 (in basin above 936 mbsf), C0004, and C0006 (red lines). Blue line = estimate for older accretionary prism formation below 936 mbsf at Site C0002.

Thermal Regime

Acquisition of a transect of good quality downhole temper-ature profiles and thermal conductivity data were an important part of Stage 1 drilling. Thermal regime may be closely tied to fault stability criteria (Hyndman et al., 1995), and the prediction of temperature at plate boundary fault zone depths is dependent on well-defined heat flow and thermal properties. Prediction of temperature at deeper levels is also crucial for future deep well planning and the mechanical specifications of long-term borehole instruments to be installed during NanTroSEIZE Stage 4, because operating temperature places severe constraints on available instruments.

Downhole temperature measurements using the APCT3 and Davis-Villinger Temperature Probe (DVTP) were successfully conducted across the Stage 1 transect. For details of the data from each site, see the respective site chapters in the Expedition Report (Kinoshita et al., 2009). In general, good linear gradients indicative of predominantly conductive heat flow were found at all sites, with the exception of some depths at Site C0006.

From SE to NW (i.e., seaward to landward along the transect), the results are as follows. In the frontal thrust region at Site C0007, the thermal gradient is 42°C km^{-1} (heat flow of 53 mW m^2). At the nearby Site C0006, a thermal gradient of 27°C km^{-1} (heat flow of 33 mW m^2) was computed. This is surprisingly low relative to regional data and the other sites. Moving to the mega-splay sites, we find the best fitting thermal gradients were 51°C km^{-1} and 57°C km^{-1} in Holes C0008A and C0008C, respectively. Very close by at Site C0004, the measured gradient was 52°C km^{-1}. At Site C0001, the measured gradient was 44°C km^{-1} (heat flow of 47 mW m^2). In the Kumano basin, the thermal gradient at Site C0002 was 43°C km^{-1}. All of these gradients are consistently lower—by 10% to >50%—than those estimated from surface measurements (Kinoshita et al., 2008). The reason for this is not clear. The extremely low heat flow observed at frontal thrust Sites C0006 and C0007 might be related to stratigraphic or structural fluid pathways developed in this region, perhaps facilitating circulation of seawater down into the thrust sheet, though geochemical evidence of seawater circulation was not identified in porewater analyses at those sites. Also, lower heat flow relative to that predicted by surface probe measurements is consistent across all the sites, even those where such circulation seems less likely. The measured gradients appear to be very nearly linear over the depth range of the available data, so discrepancies between borehole and surface measurements are probably not attributable to an advective component. The borehole vs. surface heat flow discrepancy remains enigmatic.

Conclusion

Major scientific accomplishments of NanTroSEIZE Stage 1 include the following:

Successful core sampling of the presumed aseismic portions of major faults and the near-fault environment at the mega-splay fault system and the frontal thrust area;

In situ measurements of physical properties and borehole imaging with LWD instruments, documenting present-day horizontal stress orientations through borehole breakout interpretation; and

Documenting of the lithology, structural features, and age of sediments in and below the thrust sheets, fault zones, slope cover, and forearc basin. In particular, age determination of the forearc basin fill, slope cover, and sections overridden by thrusts provides a framework for understanding the materials and processes in the seismogenic zone, by providing information on its development and evolution.

As these were the pioneering IODP expeditions for *Chikyu*, the tremendous amount of technically-challenging drilling that was accomplished is a testament to the skill of the drilling and operations teams on board and in support onshore. The scientific goals of the NanTroSEIZE transect have been framed from its earliest conception as a comparison of the properties and state of faults and wall rock between the shallow aseismic portion and the deeper, seismogenic system. Taken as a whole, the NanTroSEIZE Stage 1 transect of sites has documented the structure, sedimentology, tectonic history, present-day stress conditions, hydrologic and geochemical regime, and other aspects of the margin for the region shallower than ~1400 m below seafloor. Thus the crucial first part of the comparison has been achieved, setting the stage for deep riser drilling to the seismogenic zone.

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Magnetic Viscosity for Cyclostratigraphic Logging of Argillaceous Sediment

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Introduction

Magnetic susceptibility (MS) is currently used as a directly representative proxy for the study of climatic variations, and for cyclostratigraphic studies. It depends on the concentration of magnetic minerals in the rocks, but does not allow identifying the magnetic minerals. In the case of argillaceous sediments, the paramagnetism of clay particles often plays a major role in determining the magnitude of their magnetic susceptibility, while the presence of ferrimagnetic iron oxides or sulfides cannot be assessed using susceptibility measurements alone. Among the different methods that can be used to detect ferrimagnetic particles magnetic viscosity (MV) characterizing the delay corresponding to the acquisition or loss of induced magnetization, has the same advantages as MS. Its measurement is direct, rapid and has been proven to be very efficient in detecting the presence of secondary ferrimagnetic minerals in soils. A MV measurement technique was tested on cores taken from a borehole, in Callovian-Oxfordian formations in the eastern Paris Basin (France) (Fig. 1). Although the MV values are very small, they have cyclic variations of which strongest values are found at the base of the Lower Oxfordian. These values, when correlated to MS, Gamma Ray (GR) and a sequential interpretation of a borehole drilled close-by are found to be associated with the maximum clay fraction in the core samples, a MS maximum, and a major transgression event. Consequently, a significant increase in ferrimagnetic minerals can be associated with this event.

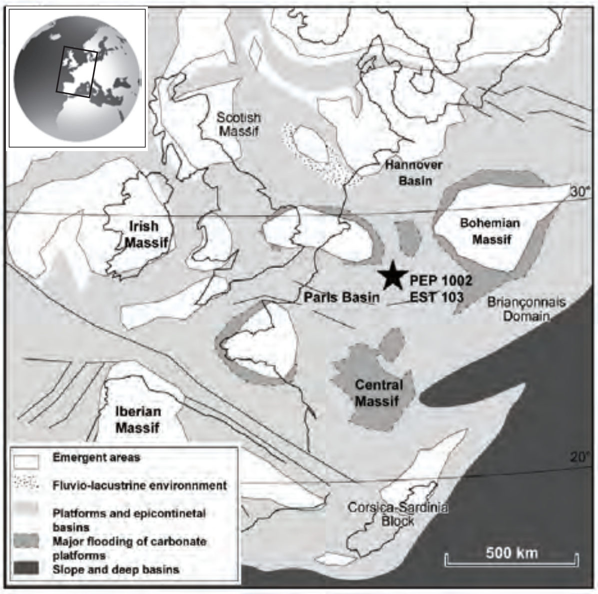

Figure 1. Paleogeographic map of the Paris Basin (indicated by stars) and surroundings (modified after Pellenard, 2003 and Dercourt et al., 1993).

Spectral analysis of the high resolution MV and MV/MS records reveals dominant patterns, identified as 95 ky eccentricity cycles, identical to those found using MS and GR analysis. Magnetic viscosity, which is sensitive to specific ferrimagnetic grains, thus appears to be a well suited proxy for cyclostratigraphic analysis, adapted to the Mesozoic homogeneous argillaceous series. Its sensitivity is complementary to, and extends the abilities of, magnetic susceptibility.

Cyclostratigraphy constitutes a remarkable tool to estimate the duration of sedimentary sequences. The method depends on the existence of climatic proxy records, whose high-resolution acquisition enables temporal resolutions to the scale of Milankovitch cycles (i.e., eccentricity, obliquity, and precession cycles with durations of 405 ky, 95 ky, 40 ky, 20 ky, and 18 ky). The quality of the records is often sufficient to allow the cyclostratigraphic series to be correlated with theoretical astronomical forcing over the past 40–60 My (Laskar et al., 2004). In such studies, magnetic properties—in particular the magnetic susceptibility (MS)—are powerful tools for cyclostratigraphic analysis (Crick et al., 2000; Latta et al., 2006). The properties, concentration, and grain size of the magnetic minerals are affected by erosion, transport, sedimentation, and/or diagenesis. MS fluctuations in a sedimentary sequence can thus reflect paleoclimatic variations and provide a record of orbital cycles. This technique has been frequently used in recent cyclostratigraphic studies; it is also a very promising diagnostic tool for the analysis of Mesozoic series (Weedon et al., 1999; Huret, 2006; Boulila et al., 2008a, 2008b). MS can be measured at low cost with a very high resolution on core samples, or by downhole logging with a high sampling rate, of the order of one centimeter. The measurements can be made in a few seconds on core, and they are simple to implement and non-destructive. The MS in argillaceous sediments is generally dominated by paramagnetic minerals, although a significant fraction of ferrimagnetic iron oxide or iron sulfide grains may also contribute. In question is however whether the ferrimagnetic fraction is more sensitive to climate changes, and thus more reliable in cyclostratigraphic studies.

It is possible to determine the presence of ferrimagnetic grains by computing the remanent magnetization, if the total field and the MS logging analysis are combined (Desvignes et al., 1992), either by measuring the magnetic viscosity (MV). Our aim was to assess the use of MV in mineralogical and sedimentological change interpretations. We tested the method on samples from the PEP 1002 borehole (Andra Underground Laboratory, France) and compared the observed MV variations with those determined using MS and sedimentology.

Magnetic Viscosity

When an external magnetic field is applied to a material, it acquires an induced magnetization with a delay which can be measured. In the case of an AC-applied field, this delayed reaction is described by a complex susceptibility: $\kappa = \kappa_{ph} - i\kappa_q$ in the frequency domain. In the time domain, for an applied step impulse function, this delay corresponds either to an increase in magnetization after the applied field has been switched on, or to a decrease in magnetization after it has been switched off. Magnetic viscosity has been observed experimentally for a wide variety of rocks, from soils (Mullins and Tite, 1973) to oceanic basalts (Trigui and Tabbagh, 1990). Theoretical approaches (Néel, 1949, 1950; Mullins and Tite, 1973) have established that for single domain grains and for wall displacement induced by thermal fluctuations in massive multi-domain grains, a quantitative relationship exists between the quadrature susceptibility (κ_{qu}, where ω is the angular frequency and κ_{td} is the time domain susceptibility) the decrease of in-phase susceptibility as a function of frequency, and time domain susceptibility variations:

$$\frac{2}{\pi}\kappa_{qu} = -\frac{\partial \kappa_{ph}}{\partial \ln \omega} = \frac{\partial \kappa_{td}}{\partial \ln t}$$

This relationship has been experimentally verified (Bloemendal et al., 1985; Dabas et al., 1992) in the presence of hyperfine grains. The role of hyperfine grains, at the transition between the superparamagnetic (SP) and stable single domain (SSD) states, has been confirmed (Dearing et al., 1996; Worm, 1998) and has been demonstrated to be very significant in soils with grain sizes below 30 nm as an indicator of the presence of secondary ferrimagnetic minerals (SFM).

In sediments, the MS corresponds to the sum of the contributions from paramagnetic and ferrimagnetic minerals, while the MV is affected only by single domain hyperfine grains. Therefore, the ratio MV/MS can be used to normalize with respect to the total magnetic particle content.

Geological Context at the Studied Boreholes

The studied boreholes truncate the Callovian-Oxfordian formation of the eastern Paris Basin (Fig. 1). They comprised homogeneous argillaceous series (around 130 m thick) deposited in a marine shelf environment. This formation is included in a second-order transgressive/regressive cycle (Hardenbol et al., 1998), with a maximum flooding surface situated near the base of the Oxfordian stage in the Mariae zone (Pellenard et al., 1999; Pellenard, 2003; Ferry et al., 2007). MS studies of many boreholes at the Bure site show that this evolution reflects the major transgressive/regressive changes of second and third orders, in which the transgressive phase is represented by an increase in MS and the regressive phase corresponds to a decrease in MS (Huret, 2006).

The rocks consist of approximately 50% clay minerals, 25% silt (quartz, feldspar, muscovite), and 25% carbonate (calcite and dolomite) whereas micas and pyrite are minor constituents (<5%). The MS is influenced mainly by the paramagnetic clay minerals and partly by ferrimagnetic minerals; significant concentrations are situated at the Callovian-Oxfordian boundary and in a clay maximum at the base of the lower Oxfordian (Esteban et al., 2006).

Two data sets from boreholes in this stratigraphy were used. The PEP 1002 borehole in the Callovian-Oxfordian argillaceous formation was accessed via the floor of the Bure Underground Laboratory at the depth of 490-m. This 19-m-long borehole is vertical. The studied interval covers approximately the top of the upper Callovian and the base of the lower Oxfordian (Fig. 2). The EST 103 hole was drilled on the Bure site, at a distance of approximately 200 m from the PEP 1002 borehole. The time interval of the EST 103 borehole could be defined as ranging from the top of the upper Callovian to the base of the lower Oxfordian (Thierry et al., 2006), by evaluating ammonite deposits. The clay content, GR value, and MS value maxima occur at depths of approximately 500 m in the EST 103 borehole and 490+3 m in PEP 1002. This corresponds to the maximum flooding surface (MFS).

Measurements and Data Processing

When the MS2B (Bartington Ltd) dual-frequency instrument was used, no difference was observed between the in-phase magnetic susceptibilities at 0.465 kHz and 4.65 kHz. This means that the quadrature susceptibility is smaller than 6.8 x 10^{-7} S.I. (for frequency dependent susceptibility of 1%, and a low frequency susceptibility of 10^{-4} S.I.). Thus, we chose the more sensitive time-domain electromagnetic technique (TDEM). A 0.084-m-diameter coincident loop sensor was built in order to be able to surround the core. Measurements were performed with TS6 electronics (Protovale Oxford Ltd), with a 2-cm sampling interval. The data were digitally recorded with thirty values stacked at each measurement point. To correct for thermal and electronic drifts, we took zeroing calibrations at regular intervals.

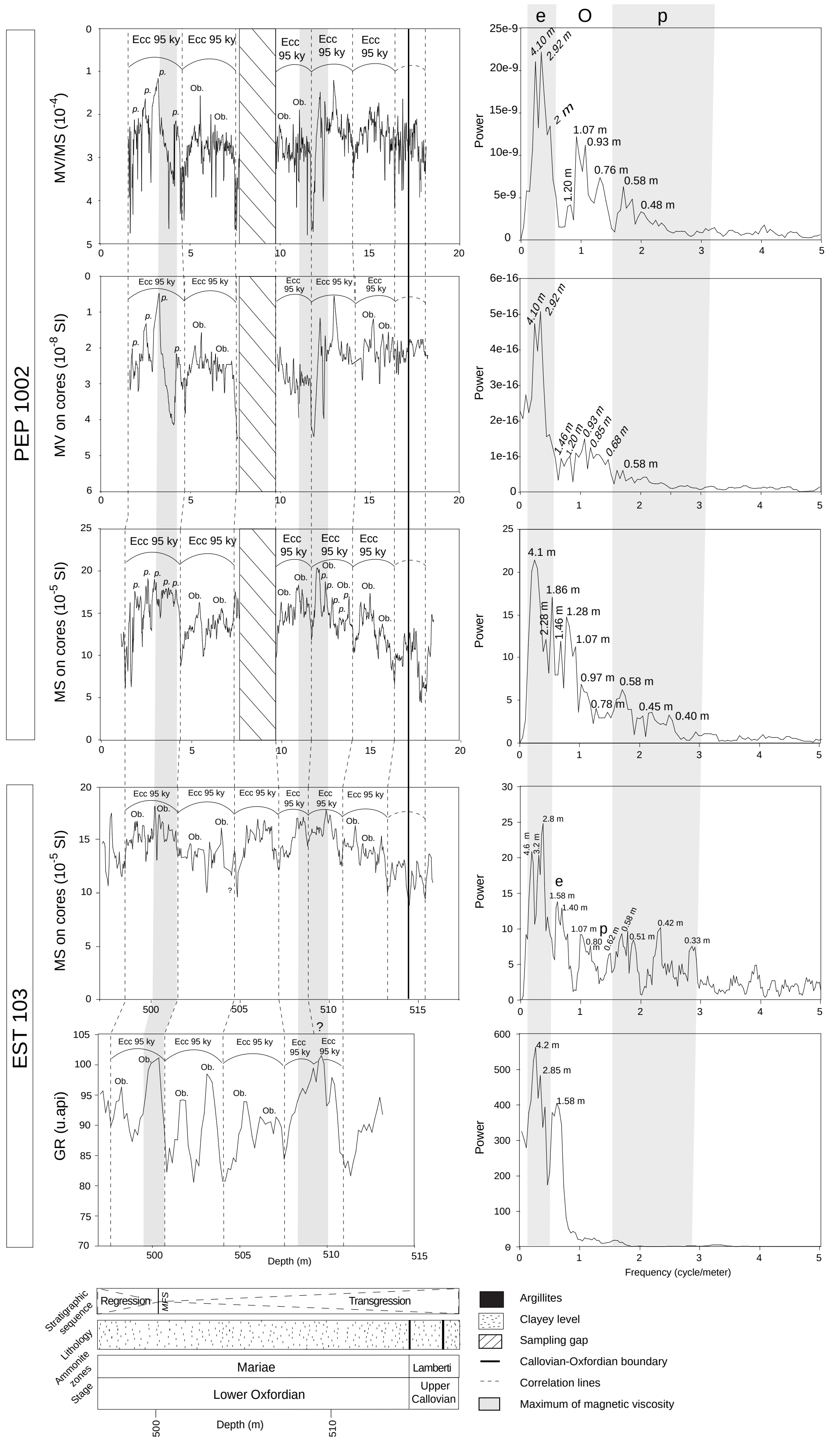

Figure 2. Biostratigraphy (Thierry et al., 2006), lithology (Huret, 2006), sequence stratigraphy interpretation and analysis of Gamma Ray (GR) well logging, and Magnetic Susceptibility (MS), Magnetic Viscosity (MV) and MV/MS ratio of the EST 103 and PEP 1002 boreholes. The light grey bands indicate zones with the strongest MV values. Presentation of 2π –MTM power spectrum after trend rejection. Identification of orbital cycles in the recordings (3 point smoothing of the MS and MV curves), symbols: eccentricity 95 ky (e), obliquity (O) and precession (p).

As the core is not continuous and presents some fractures and gaps, the data had to be corrected for these effects. The signal decay was computed as a function of core length, using an abacus, for several gap sizes. The final data reduction step involved transforming the measured voltage into apparent quadrature susceptibility, after calibrating the global loop and instrument response using a small 5-mm-diameter metallic sphere (Tabbagh and Dabas, 1996). In order to provide a good fit for the experimental values, the total instrument sensitivity was increased so that its total dynamic range corresponded to 10^{-7} S.I., in good agreement with the absence of a measurable frequency dependence of the MS2B instrument.

Magnetic Viscosity Results

The MV log is presented in Fig. 2, together with the MS (2-cm sampling interval), the MV/MS ratio recordings, and the GR (10-cm sampling interval) and the MS (4-cm sampling interval) recordings from the EST 103 borehole. These recordings are correlated with the biostratigraphic data. The values of MV we obtained are very low (<5 x 10^{-8} S.I.), which is roughly 100 times lower than in soils (Thiesson et al., 2007). This result can be explained by the very small secondary ferrimagnetic mineral content (possibly due to Fe^{++} ions dissolved in water during deposition and compaction).

The long-term evolution and high-frequency variations of the MS are similar between the EST 103 and PEP1002 boreholes. The MS maxima in the PEP 1002 hole are located at depths ranging from 3 m to 5 m, and those between 10 m and 13 m are correlated with strong GR values characterizing clay-rich zones. Moreover, the GR log presents the same high frequency variations as the MS recording (Fig. 2). These similarities confirm that the presence of paramagnetic clay minerals is the dominant contributor to MS. Correlations between MV and MS are less evident, although they present the same cyclic variations (of the order of 3 m in thickness). They appear to be anti-correlated, rather than correlated; nevertheless, the strongest MV values, which occur at 3.5 m, 7.5 m, and 11–13 m, correspond to maxima of both MS (values varying, 15–20 x 10^{-5} SI) and GR (Fig. 2). It should be noted that the relative variations in MV (variations divided by the mean value) are clearly higher than those in MS.

The main discrepancy, together with the main high and medium frequency variations observed in the MV, lies between 3 m and 4 m. This is associated with a strong relative increase in MV, followed by a strong relative decrease. By comparison, the sedimentology and stratigraphical information corresponds to a MS maximum and, after comparison with the EST103 borehole, is found to be correlated with the position of the second-order maximum flooding surface (MFS) known to exist at the base of the Lower Oxfordian. This level also corresponds to a clay-rich maximum in the EST 103 borehole, with strong GR values. A second interval with strong MV, MS, and GR values is observed between the depths of 11 m and 13 m, but is not associated with a particular lithological or stratigraphical change. However, the base of the Mariae zone can be recognized as the most argillaceous level of the series (Pellenard et al., 1999; Esteban et al., 2006).

The highest MS values, found at 3 m depth in the PEP 1002 borehole, indicate that the MFS may correspond to (i) a greater quantity of paramagnetic clay particles, or (ii) a greater quantity of magnetite grains of terrigenic origin (Esteban et al., 2006), or (iii) greater *in situ* generation of biogenic minerals (greigite or magnetite). The strong changes in MV suggest that the processes involved are even more complex than suggested by MS alone; inside this period of high susceptibility, rapid and strong changes occurred in the sediment transfer modes, and possibly in the oxygen content of water. In the absence of a detailed mineral analysis, it is not possible to determine exactly what happened during the flood event.

We would like to emphasize that, for the MFS event recorded at 3–4 m, the MV/MS ratio provides a large quantity of useful information. It not only highlights changes that have already been observed using GR or MS, as for the case just above 11 m, but also reveals more complex, detailed variations which have yet to be understood. As the relative variations in MS are of limited extent (20% maximum) and are correlated with clay content, the MV/MS ratio can be initially interpreted as expressing the small ferrimagnetic particle content of the clay. Variations in this ratio could thus provide an indication of the sediment's origin.

Frequency Content

MV data exhibited a higher relative variability than that recorded using MS (or GR). However, in order to assess its relevance for cyclostratigraphic studies, the frequency content of the relevant recordings must also be analyzed.

Time series analysis of the PEP 1002 and EST 103 well logs and core data were carried out using the "Multi-Taper Method" (Thomson, 1982, 1990). This method, which we implemented with Matlab® software, estimates the power spectral density of a time series through the application of a set of orthogonal tapers, while maintaining suitable confidence levels. In spite of the presence of some gaps in the PEP 1002 data and of the limited length of the recordings, our analyses were performed over the full series. The data was re-sampled every 2 cm, using linear interpolations (except for the GR, which has a constant sampling step), and the linear trend was removed. The results are shown in Fig. 2, for which the data was smoothed (3-point average) to improve the contrast of the high frequency variations.

Identification of the orbital cycles was achieved using the frequency ratio method (Mayer and Appel, 1999), which consists of comparing the frequency ratio of pairs of dominant cycles observed in the series, with those known to characterize the Earth's orbital cycles (i.e., 18.2 ky and 21.9 ky for precession, 37.7 ky for obliquity, and 95 ky for eccentricity) during the Jurassic period (Berger and Loutre, 1994). GR analysis of the EST 103 reveals a power spectrum with only two major peaks, with periods of 2.85 m and 4.2 m, and a weaker peak at 1.58 m, visible on the curve (Fig. 2). This power spectrum does not have small high-frequency variations similar to those associated with the MS data, because a longer (10 cm) sampling step was used. The MS spectrum of the EST 103 hole presents several peaks with strong amplitudes, the first identical in frequency to those of the GR spectrum, with periods between 4.6 m and 2.8 m clearly visible (Fig. 2). Others periods, close to 1.4 m and 1.58 m, 1.07 m and 0.8 m, and 0.62 m and 0.33 m, are also characterized by comparatively strong amplitudes. By comparing the terrestrial orbital frequency ratios with those derived from the GR and MS recordings at the EST 103 hole (Table 1), we can associate the core cycles (with periods of 2.8–4.1 m) with 95-ky eccentricity cycles. The core cycles with periods of 1.58–0.62 m can be associated with obliquity cycles, and the core cycles with periods 0.33–0.80 m can be associated with precession cycles. These periodicity allocations agree with the cyclostratigraphic analysis performed on cores of another hole (EST 322) drilled 10 km from EST103 and PEP 1002 (Boulila et al., 2008b). The fact that the observed cycles are spread over a large range of frequencies can be explained by variations in the rate of sedimentation. The sedimentation rate, in the MS recordings associated with 95-ky eccentricity cycles, increases from that corresponding to the 2.8–3.2 m thicknesses at the bottom of the recording, to that resulting in a thickness of approxi-mately 4 m at the top (Fig. 2).

Table 1. Durations and duration ratios of orbital cycles, defined for the Late Jurassic (Berger and Loutre, 1994), frequency ratios of the principal cycles observed in MS and GR recording spectra from the EST 103 hole, and of the principal cycles observed in MS, MV and MS/MV recording spectra from the PEP 1002 hole.

		Precession	**Obliquity**	**Eccentricity**	**P/O**	**P/E**	**O/E**
Orbital Cycles (Later Jurassic)		18.2 ka 21.9 ka	37.7 ka	95 ka	0.483 0.581	0.191 0.230	0.397
		Dominant Periods			Ratio		
Intervals		a	b	c	a/b	a/c	b/c
EST 103	GR		1.58	4.10			0.385
	MS	0.33 0.58 0.80	0.62 1.07 1.40	1.58 2.80 3.20	0.532 0.542 0.571	0.209 0.207 0.250	0.419 0.382 0.437
PEP 1002	MS	0.40 0.58	0.78 0.97	1.86 2.28	0.513 0.597	0.215 0.254	0.419 0.425
	MV	0.58	1.20	2.92	0.483	0.199	0.411
	MS/MV	0.48 0.58	0.93 1.20	2.00 2.92	0.516 0.483	0.240 0.199	0.465 0.411

The spectral analysis of MS in PEP 1002 is more complex. Eccentricity cycles are expressed, as for the EST 103 borehole, by a 4.1-m thickness. However, other cycles such as obliquity and precession are more difficult to identify because the spectrum contains many close frequency peaks with strong amplitudes. This effect is certainly amplified by the presence of a core sample gap (7.76–9.26 m). Similar spectral characteristics have already been observed by Weedon (1989); however, the frequency ratio of the major peaks allowed Milankovitch cycles to be identified with frequencies in agreement with those found at the EST 103 borehole (Table 1). MS stratigraphic correlations between the two boreholes show similar trends and clearly present the same high-frequency cycles. In this correlation, some thickness variations are also expressed by small differences in MS measurements.

The MV spectrum for PEP 1002 in Fig. 2 is clearer than that produced from the MS recordings. It has the same two strong peaks corresponding to periods of 2.92 m and 4.1 m, associated with the 95-ky eccentricity cycles. Although the higher frequency cycles are not very strong, the use of frequency ratios enabled obliquity and precession cycles to be identified. The spectrum of the MV/MS ratio is the most representative of all the spectra, with all Milankovitch cycles expressed with strong, distinct amplitude peaks. The MV and MV/MS curves (inversed in Fig. 2) clearly show the eccentricity cycles corresponding to thickness periods in the range of 2 m to 4 m.

Conclusions

The results presented in this paper are the first on direct magnetic viscosity measurements of argillite samples. Measurements of PEP1002 cores are shown to be informative, and they demonstrate that MV measured by the TDEM technique appears to be a potentially promising climate proxy for high-resolution cyclostratigraphic studies. The resolution and lateral sensitivity of MV measurements should be similar to that of MS and could be adjusted by appropriate definition of the coil geometry. The potential of MV as a proxy for stratigraphic climate analysis is its ability to constrain the ferromagnetic iron oxide or sulfide grain fractions. This capability potentially can be used to improve the identification of sedimentary sources, changes in mineralogy which occurs during transport, and sedimentation process. It is now necessary to determine precisely the advantages and drawbacks of this type of measurement and the extent to which it can be complementary to MS and other petrophysical analyses. The construction of a MV wire-logging tool could take advantage of the experience acquired in surface prospecting instruments.

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Drilling for the Archean Roots of Life and Tectonic Earth in the Barberton Mountains

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Introduction

In the Barberton Scientific Drilling Program (BSDP) we successfully completed three drill holes in 2008 across strategically selected rock formations in the early Archean Barberton Greenstone Belt, South Africa. This collaborative project's goal is to advance understanding of geodynamic and biogeochemical processes of the young Earth. The program aims to better define and characterize Earth's earliest preserved ocean crust shear zones and microbial borings in Archean basaltic glass, and to identify biogeochemical fingerprints of ancient ecological niches recorded in rocks. The state-of-the-art analytical and imaging work will address the question of earliest plate tectonics in the Archean, the $\delta^{18}O$ composition, the redox state and temperature of Archean seawater, and the origin of life question.

The BSDP project serves as a first phase towards a large-scale deep drilling project which will also encompass the development of a local Earth science research and education center. During the period July–August 2008, a first phase of drilling yielded three boreholes with a total of 800 m of core with 99% core recovery in the early Archean Barberton Greenstone Belt (BGB), South Africa. Five decades of scientific research on the 3.5–3.1-Ba-old BGB has established the mountain ranges of Barberton as a world heritage site and a focus for international scientists interested in early Earth processes. The rocks around Barberton are unique in that they represent relatively intact and undisturbed remnants of preserved ancient seafloor and continental crust that have largely escaped tectonometamorphic reworking since the time they formed (Schoene et al., 2008).

Outstanding questions about early Earth—as well as Earth systems and linkages between physical, chemical, and biological processes operating within and on the early Earth—include the following areas of interest:

- plume-driven versus plate-tectonic-driven mechanisms for the early Archean
- Earth's early magnetic field and exogenous influx from space
- volcanology, origin of komatiites, and thermal gradients on early Earth

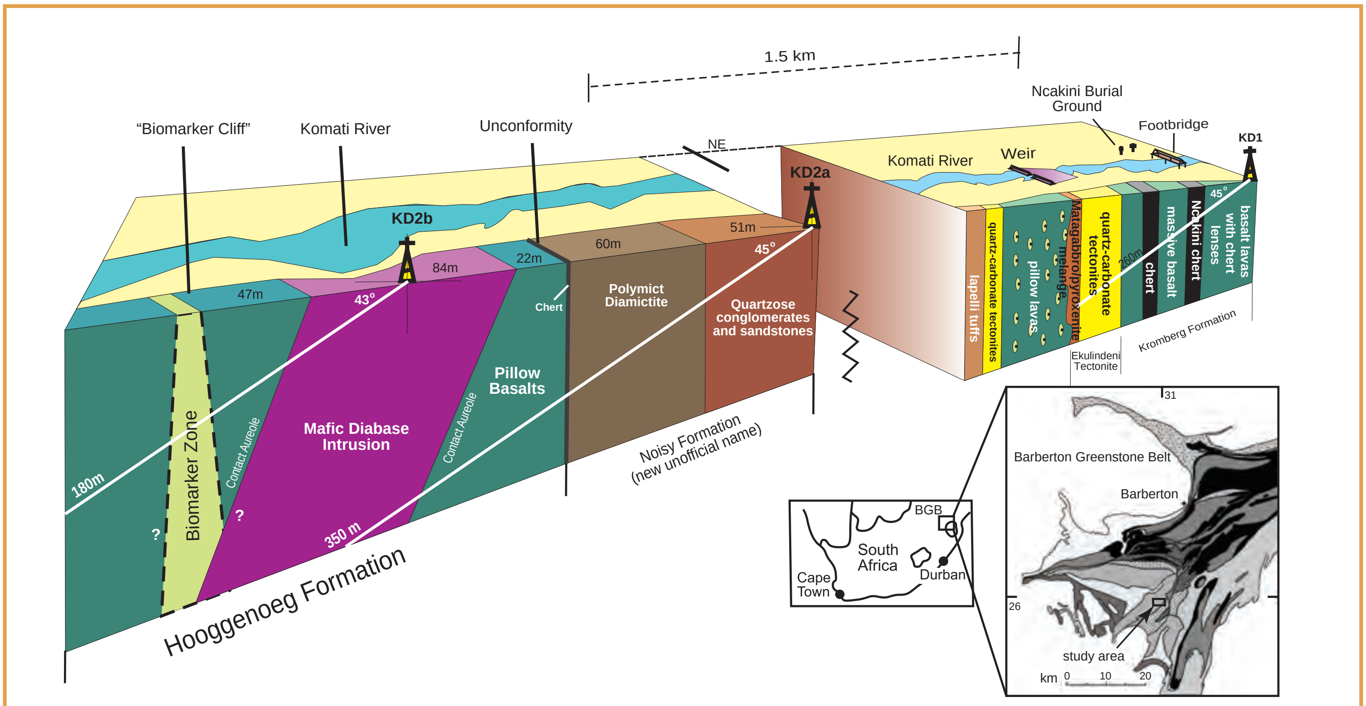

Figure 1. Three-dimensional block diagram with simplified geology depicting the positions and shallow drilling angles at drill sites KD1, KD2a, and KD2b and location maps of the study area with South Africa and simplified geology of Barberton Greenstone Belt (BGB map modified from Kareem, 2005).

- chemical, structural, and tectonic make-up of the oldest greenstone belts
- crustal and mantle fluid processes, chemistry of ancient seawater composition
- climate and atmospheric conditions at 3.4–3.5 Ga
- origin of life and early life-sustaining environments

Addressing these topics using surface samples has, however, been plagued by a number of complications related to limited exposure and secondary processes like weathering.

Diamond core drilling, which retrieves fresh, representative samples from depth at strategic locations, has the advantage of providing continuous information with depth, and avoiding a number of complexities related to surface processes.

Geological Background and Drill Site Locations

The BGB forms part of the easternmost margin of the Kaapvaal Craton as a NE-SW trending tectono-metamorphic belt. Traditionally, rocks in the southern part of the belt have been ascribed to the 3.2–3.5 Ga Swaziland Supergroup, which in turn has been further subdivided into the Onverwacht, Fig Tree, and Moodies Groups (Viljoen and Viljoen, 1969; Brandl et al., 2006). Drilling was aimed at focusing on the mostly tholeiitic basalts of the 3.47–3.44-Ga mid-upper Onverwacht Group of the Swaziland Supergroup in the southwesternmost BGB (Fig. 1). Drill sites are located in the Songimvelo Nature Reserve, near Ekulindeni (Kromdraai). The exposed rocks include the Mendon, Kromberg, and Hooggenoeg Formations of the Onverwacht Group.

The first hole (KD1, S26°02'15.3", E31°00'00.0", total depth of 261 m) allowed sampling into the Upper Kromberg Formation, a section of pillow lavas and sheet flow with interlayered cherts and chert xenoliths that overlies an enigmatic early carbonated and silicified oceanic shear zone known as the Ekulindeni Shear Zone. Drilling stopped in pyroxenitic units just beyond a carbonated shear zone. Studies on core samples will allow definition of the chemical alteration and microbial activities from an Archean marine bottom-surface into its underlying sub-surface fault zones. Results will also help to reconstruct the chemical composition and temperature of the associated seawater.

The second and third holes (KD2a, S26°01'50.0", E30°59'32.6" and KD2b, S26°01'25.3", E30°59'16.6", total depths of 350 m and 180 m, respectively) are located about 1.5 km farther NE along the Komati river on a flat open river terrace. The main objective of these holes was to drill across a basal unconformity in the Hooggenoeg Formation between a set of subaerial siliciclastics consisting of diamictites, conglomerates, and sandstones and underlying basaltic pillow lavas with interbedded cherts. Although these conglomerates were formerly placed in the Hooggenoeg Formation by Viljoen and Viljoen (1969), ongoing geological mapping in the area has lead to a revised stratigraphy (de Wit et al., in prep.). The pillow lava basalts in the Hooggenoeg Formation contain early Archean biomarkers or ichnofossils described by Furnes et al. (2004), in the type area known as the "Biomarker Cliff". Field and preliminary core observations suggest that in this site the top of the pillow lava pile was exposed to the Archean atmosphere at the unconformity. To avoid an 84-m-thick mafic/diabase intrusion about 22 m away from the unconformity, we relocated the drill rig for a third hole (KD2b) 172 m further north (Fig. 1). Drilling at KD2b intercepted the type section for the biogenic structures that occur in pillow lava margins and typify Earth's 3.4-Ga oceanic environments, including an early hydrothermal ocean-floor-type metamorphic overprint (Furnes et al., 2004). This part of the section will allow the physio-chemical conditions of the biological communities in the pillow margins and their preservation window to be better defined.

Figure 2. Drill rig aligned and set to drill at the shallowest possible angle (45°) relative to the dip and dip direction of the steep near-vertical orientation of the geological units along the Komati River. The >3-m-long rod is composed of basalt or diamictites.

Drilling Methods

The drill rig was oriented perpendicular to the bedding or structural orientation of the lithological units, using the average strike and dip readings of rock outcrops at the site.

Given the steep, generally vertical orientation of the geologic units, drilling for all three boreholes was carried out at the shallow angle of about 45° and a drilling direction towards 320° to 340° (Fig. 2). Drilling at shallow angles raised a number of difficulties, including borehole wall collapses in the alluvial overburden. Due to frictional drag of the inner tube on the inside of the drill stem rods, the elapsed time between runs increased significantly as a consequence of the flat angle. The overshot instrument attached to the wire-line for lowering the innertube down the hole was modified with a heavy metal rod weight to overcome frictional energy downhole to shorten down time and to facilitate efficient latching of the innertube onto the core barrel. The potentially delicate nature of bio-textures and chemical biomarker (carbon) signatures to be encountered made it vital not to alter the original Archean chemistry of the drilled rock. Furthermore, since data on the redox state of the Archean atmosphere and seawater composition is one of the analytical goals, reducing oxidation was imperative. Therefore, a number of steps were taken during the drilling project to ensure that the original rock chemistry remained as intact as possible.

- Only clean water was used as drilling mud.
- A clean drill rig was used and repeatly washed, and the site was kept clean of potential contaminants including smoke at all times.
- Only one person handled, washed, and dried all core immediately after retrieval.
- Cores were packed in wooden boxes with wood chips for support during shipping.

Core recovery for all three holes was typically above 98% providing up to 3-m rods of core (Fig. 2). Only in the case of intercepting the first chert horizon, namely the "Footbridge Chert" in KD1, did core recovery temporarily drop to 92% due to partial fracturing of the chert. Initial stages of each hole involved emplacement of HQ (63.5-mm diameter) size metal casing to stabilize the hole.

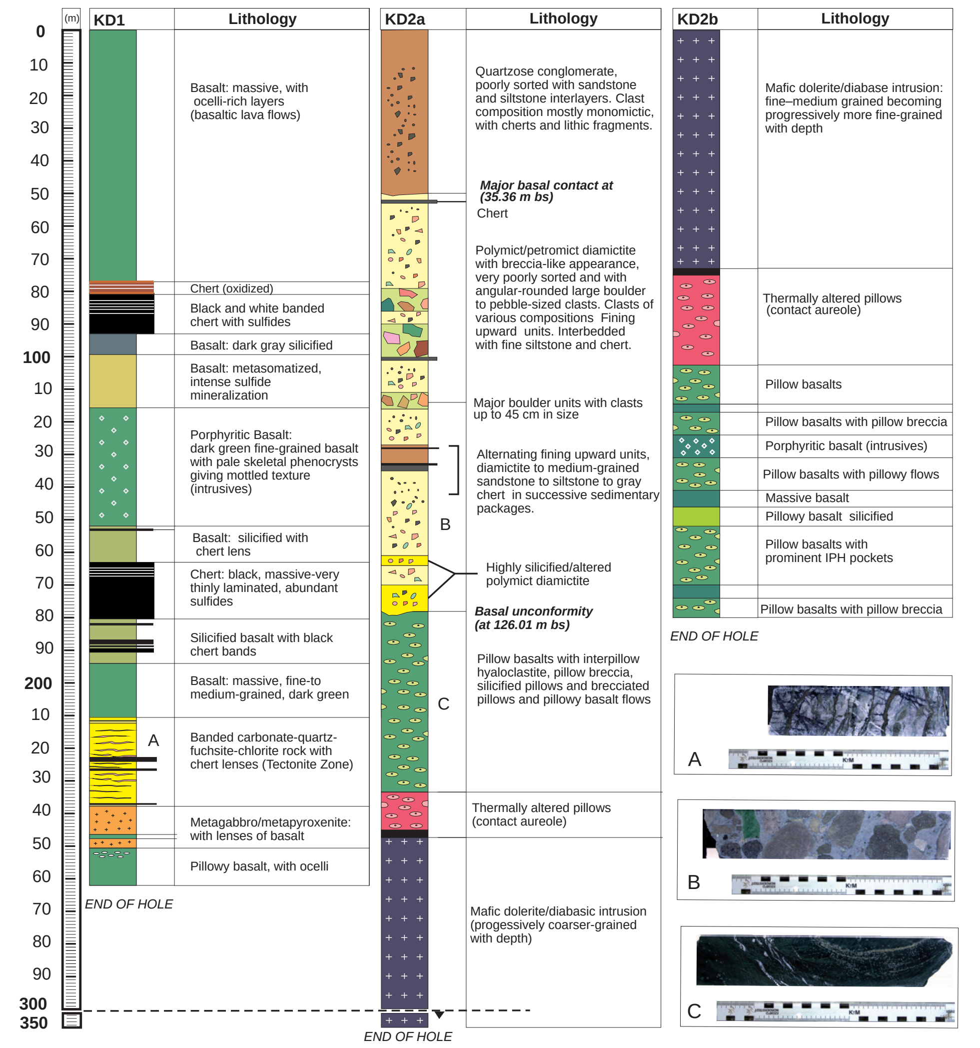

Figure 3. Simplified diagrams of geological logs for KD1, KD2a, and KD2b. The labelled photographs of selected core sections in the inset [A–C] correspond to the labels indicated at different depths in the three logs. [A] Carbonate-quartz and fuchsite-chlorite bands in the tectonite zone of KD1. [B] Example of shape, size, and variety of clasts occurring in the diamictite unit that directly overlies pillow basalts at the unconformity in KD2a. [C] Drill core section through a pillow basalt consisting of an ocelli-rich pillow core, outer ocelli-poor glassy pillow rim, and veined and sulfide-bearing interpillow hyaloclastite.

Water flow rate downhole generally varied at 30–33 L min^{-1}. Optimum revolutions per minute were around 580, typical for basalts at a torque of around 3 kN. Given the flat 45° angle, the weight on the bit for the drill rig was adjusted to around 2–2.5 kN using a soft matrix NQ corebit (47.6-mm diameter). The very hard chert horizons were cored at 450 rpm. A core orientation tool was used to fix the orientation for paleomagnetic studies on basalts.

Preliminary Results

Core log data from KD1 (total length 261 m) records about 54.5 m of basalts from the Mendon Formation before the top of the Kromberg Formation was intercepted (Fig. 3). The section of drill core representing this formation includes two major chert units of about 12 m each in an 83-m-thick section of variably metasomatized and silicified massive intrusives and lava flows. The first of these chert units appears to record an

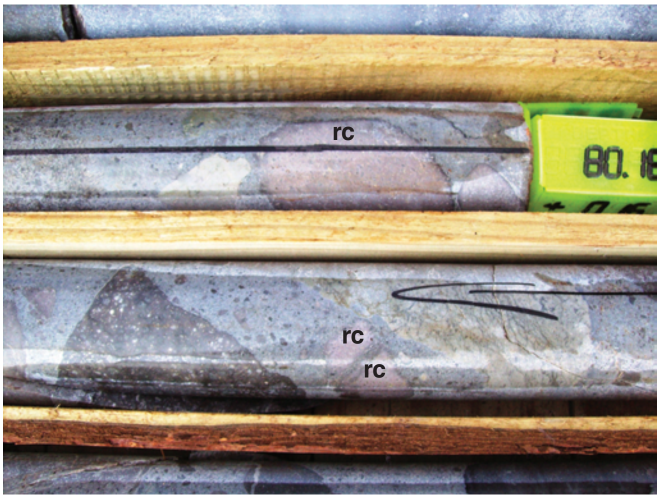

Figure 4. Distinct chemical weathering rim around light pink rhyolitic clasts (rc) possibly recording weathering conditions and/or redox conditions on the early Earth's surface.

upper 2.5-m-thick oxidized horizon, followed by an 8.5-m lower part consisting of black massive occasional white banded chert containing sulfides (implying a more reduced environment). The second chert unit was intercepted at a depth of about 115 m below surface; it occurs at the center of a 30-m-wide zone of highly silicified basalt that is generally associated with a number of discontinuous black chert lenses and veins. Near the end of KD1, a 20-m-thick zone occurs with thin black chert veins and consists of carbonate and quartz bands and veins in a matrix of dark green fuchsite (Cr-muscovite), chlorite, and magnetite. In surface outcrop this zone is as thick as 67 m, and it is adjacent to a 72-m-thick unit of highly foliated metapyroxenite. It is currently interpreted to represent a remnant component of an early oceanic shear zone. The carbonate-quartz tectonite zone, as seen in the drill core, is less than one-third of its thickness on surface, indicating discontinuous and variable thickness. Drilling stopped in a metapyroxenitic unit consisting of a melange of metagabbros and pillow basalt screens for about 17 m beyond the end of the carbonate-quartz zone. Micro- to nano-scale analysis of the rock units in KD1 will allow comparison of various potential ecological niches across an Archean seafloor environment into deeper underlying sub-seafloor tectonite zones. Such a comparison has not been previously carried out. Carbonaceous cherts in the upper and lower parts of KD1—representing marine seafloor and hydrothermal cherts, respectively—are the primary analytical target in the search for early life microtextures and chemical fingerprints in KD1. These rocks will be investigated using laser Raman microspectroscopy and bulk rock geochemical analysis. Calcite-quartz extensional veins/bands in the lower tectonite zone will be analyzed for their $\delta^{18}O$ composition to determine hydrothermal seawater fluid temperatures and water-rock ratios. These results will be integrated with *in situ* stable isotope and synchrotron X-ray analyses of individual fluid inclusions in the lower tectonite zone, combined with a micro-structural fabric analyses of deformed rocks. High-resolution Secondary Ion Microprobe Analyses of various sulphide generations present throughout KD1 aims to investigate mass-dependent and possible mass-independent sulphur isotope fractionation as a geochemical tool to identify microbial interactions and improve our understanding of the early Earth's sulfur cycle.

Drill hole KD2a penetrated a basal unconformity at around 126 m below surface, between a lower marine section of pillow lavas and interbedded cherts that are abruptly overlain by subaerial diamictites, conglomerates, and sandstones. In the drill core, clasts in diamictite units directly above the unconformity are poorly sorted, polymictic in composition, and generally angular giving the rocks a breccia-like appearance suggestive of glacial diamictites. Many of the clasts, particularly those of the rhyolitic and dacitic composition, display a prominent weathering halo or chemical alteration rim (Fig. 4). Preliminary measurement of clast size in the core indicates that the entire unit coarsens upward. Overlying these 'diamictites' are more typical fluvial facies, conglomerates, and sandstones. However, pronounced soft sediment deformation features are also present and may suggest an offshore marine turbidite facies origin. A sedimentological provenance study involving a detailed documentation of the petrological characteristics of the clasts, U-Pb dating of detrital zircons from selected depths in the core, and reconstructing a chemical weathering profile will aim at understanding of the depositional environment(s) of these enigmatic sediments and possibly constraining the atmospheric conditions on the Earth's surface at ~3.45 Ga. The lower part of drill hole KD2a penetrated a section of thermally altered pillow basalts in a metamorphic contact aureole and ended in a medium-grained mafic intrusive at a depth of 350 m.

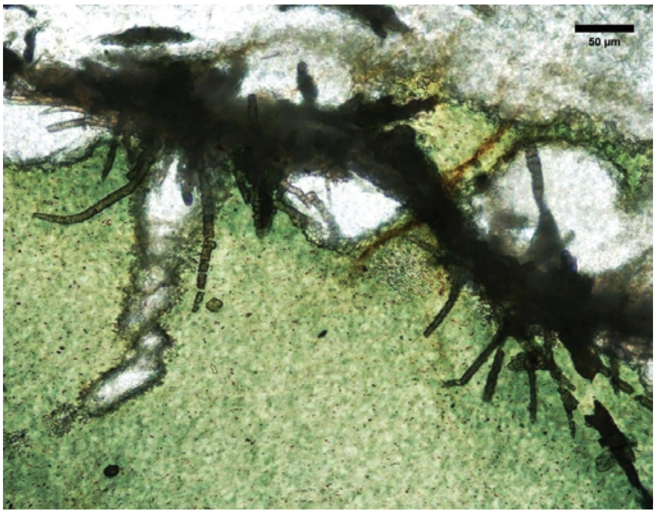

Figure 5. Photomicrograph of microbial biotextures in a surface sample of inter-pillow breccia from the Hooggenoeg Formation of the Barberton Greenstone Belt. The meta-volcanic glass comprises a greenschist facies assemblage of chlorite and quartz with titanite-filled tubular textures. These are curvilinear and unbranched, and they radiate from a central band of microcrystalline titanite. Some taper towards their ends and are segmented by cross-cutting chlorite. These textures are interpreted to be mineralized tunnels created by microbes that etched volcanic glass on the Archean sub-seafloor. This is a composite z-stacked high-resolution image showing tubes at different focal depths.

The third hole, KD2b, intercepted at depth the "Biomarker Zone" originally described in surface outcrop by Furnes et al. (2004). Detailed petrographic work on surface samples from this zone has shown a range of morphological types of ichnofossils (McLoughlin et al., 2007; see also Fig. 5). The recent *in situ* U-Pb dating of titanite infilling the microbial ichnofossils has revealed an Archean age (Fliegel et al., 2008). Pillow lavas in the drill core of KD2b will be investigated for early Archean ichnofossils from a depth of around 130 m onwards to further investigate morphological diversity and antiquity of the bioalteration textures by applying state-of-the-art analytical and imaging techniques (e.g., Raman spectroscopy, X-ray synchrotron imaging). A detailed study of the continuous drill core section recovered from depth in KD2b aims to reconstruct the spatial distribution of these microbial ichnofossils with depth through an ancient oceanic lithosphere. In addition, we aim to determine the preservation conditions of the biosignatures and the prevailing life-sustaining hydrothermal conditions that existed in the early oceanic crust.

KD2b also penetrated thermally altered pillow basalts in a metamorphic contact aureole around the northern margin of the mafic intrusion that will be used as a thermal and reversal test for paleomagnetic studies. To date, only volcanic rocks of late Archean age (~2.7 Ga) have yielded detailed paleomagnetic signatures, and we anticipate that this Barberton drill core will provide new insights into the strength of the much earlier ~3.45 Ga Archean magnetic field and the size of the young Earth's inner core.

Future Plans for Drilling in Barberton

The present drilling project serves as a preliminary stage for a more ambitious super-deep drilling project to penetrate one of two ancient crustal-scale suture zones in the BGB. A magneto-telluric transect across the BGB has been conducted over the period March–May 2009 to start identifying the target zone. This will be followed by a seismic survey and an on-site ICDP workshop to plan a proposal for deep drilling. In addition, we plan to establish an advance drilling technology school and develop a rural science education center linked to a world class 'Early Earth' museum near this drill site.

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Fig. 5. Photomicrograph by Nicola McLoughlin (CGB, Bergen)

The Laguna Potrok Aike Scientific Drilling Project PASADO (ICDP Expedition 5022)

by Bernd Zolitschka, Flavio Anselmetti, Daniel Ariztegui, Hugo Corbella, Pierre Francus, Christian Ohlendorf, Frank Schäbitz and the PASADO Scientific Drilling Team

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Introduction

In the Southern Hemisphere long, continuous, and high-resolution series of terrestrial paleoclimatic data are scarce, and they are only slowly emerging. Globally speaking, the most extreme oceanic character is encountered between 40°S and 60°S (Fig. 1). In this latitudinal belt ninety-eight percent of water is juxtaposed to only two percent of land—Patagonia and a few sub-Antarctic islands. Therefore, records from Patagonia are a key to a better evaluation of inter-hemispheric linkages and differences in the climate system, especially as the Southern Ocean plays a key role for a proper understanding of the global climate system (Kaiser et al., 2007). Moreover, this region—close to the Andean volcanic chain—is one of the source regions for southern hemispheric dust. It is also subject to shifts in polar to mid-latitude pressure fields and precipitation regimes related to the Southern Hemispheric Westerlies and the Antarctic Oscillation. Patagonia thus potentially provides unique terrestrial records of variations in (1) climate, (2) hydrology, (3) erosion and deposition of atmospheric dust, and (4) volcanic activity. Additionally, links can be established to ice cores from Antarctica and to marine records from the South Atlantic where dust and tephra of Patagonian provenance have been deposited (Ackert, 2009; Narcisi et al., 2005; Sugden et al., 2009). For southernmost South America most lake sediments extend in time not beyond the Late-Glacial. However, Laguna Potrok Aike (Fig. 1) is older than the numerous Patagonian glacial lakes and offers the opportunity for volcanological studies.

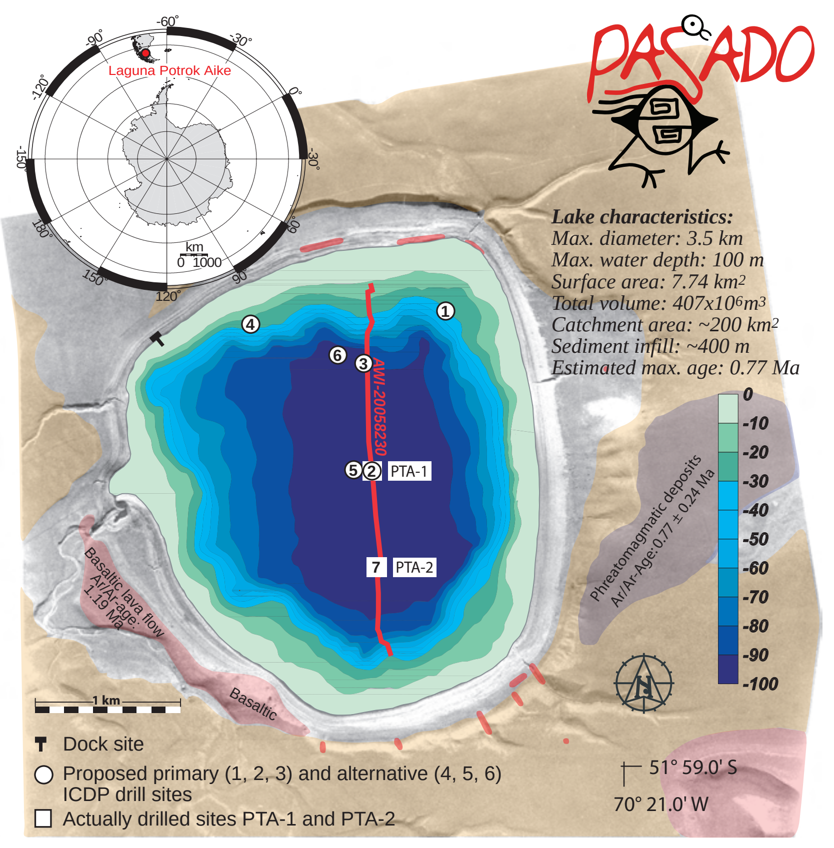

Figure 1. Bathymetric map of Laguna Potrok Aike merged with an aerial photograph and geological data (Corbella, 2002; Zolitschka et al., 2006). Inset map shows the site location in sub-Antarctic South America. Color-coded young fluvial and lacustrine deposits (gray), a mid-Pleistocene basalt lava flow (red), phreatomagmatic tephra deposits (pink), moraine till (yellow), Tertiary Santa Cruz Formation (orange), multi-channel seismic line of Fig. 2 (red line), and planned (numbered white circles) and drilled (numbered and labeled white squares) coring sites.

Laguna Potrok Aike developed in the Pliocene to late Quaternary Pali Aike Volcanic Field (Zolitschka et al., 2006). Located 100 km east of the Andean volcanic arc, this northwest-southeast oriented back arc volcanic belt is about 50 km wide and more than 150 km long. The oldest outcropping geological strata in the catchment area of Laguna Potrok Aike are Lower Miocene fine-grained fluvial sediments of the Tertiary Santa Cruz Formation (Blisniuk et al., 2005). During the Plio-Pleistocene (3.5–1.0 Ma) glaciers advanced northward from the Magellan Strait and covered the area now occupied by Laguna Potrok Aike. Thus, the surface of its catchment area today is dominated by fluvioglacial sediments and basal moraine tills of the most extensive glaciation (Coronato et al., 2004) with occasional exposures of basalts and volcanic spatter cones. The youngest glaciation that influenced the catchment area ended around 0.76 Ma (Singer et al., 2004) and left behind terminal moraines in Chile located ~20 km south of Laguna Potrok Aike. Around 0.77 Ma, a phreatomagmatic explosion was triggered, creating a maar which developed into the lake of Laguna Potrok Aike (113 m a.s.l.). The lake is 100 m deep with a maximum diameter of 3.5 km (Fig. 1), and it has a surface area of 7.74 km^2 (Zolitschka et al., 2006). The bathymetry is simple and pot-shaped, typical for a maar lake (Figs. 1, 2). The crater depression itself, only partly occupied by the lake, has a larger diameter of 5 km. Because this basin has not been scoured by young glaciations, the crater lake of Laguna Potrok Aike is an ideal site for the recovery of long paleoenvironmental and paleoclimatic records. The lacustrine sedimentary infill potentially covers several glacial to interglacial cycles up to present times; it is underlain by coarse volcaniclastic rocks deposited immediately after the phreato-magmatic maar eruptions ceased.

The maar lake, with currently episodic tributaries, must be regarded as a subsaline terminal lake with a pH of 8.8 and a salinity of 2.2‰ due to the prevailing semiarid climate in the dry steppe environment of southernmost South America (Zolitschka et al., 2006). However, geomorphologic evidence suggests that overflow occurred northward in the past. Despite its great depth and large water volume, the lake has not developed a persistent seasonal stratification today. In response to the strong westerly winds, the lake is currently polymictic.

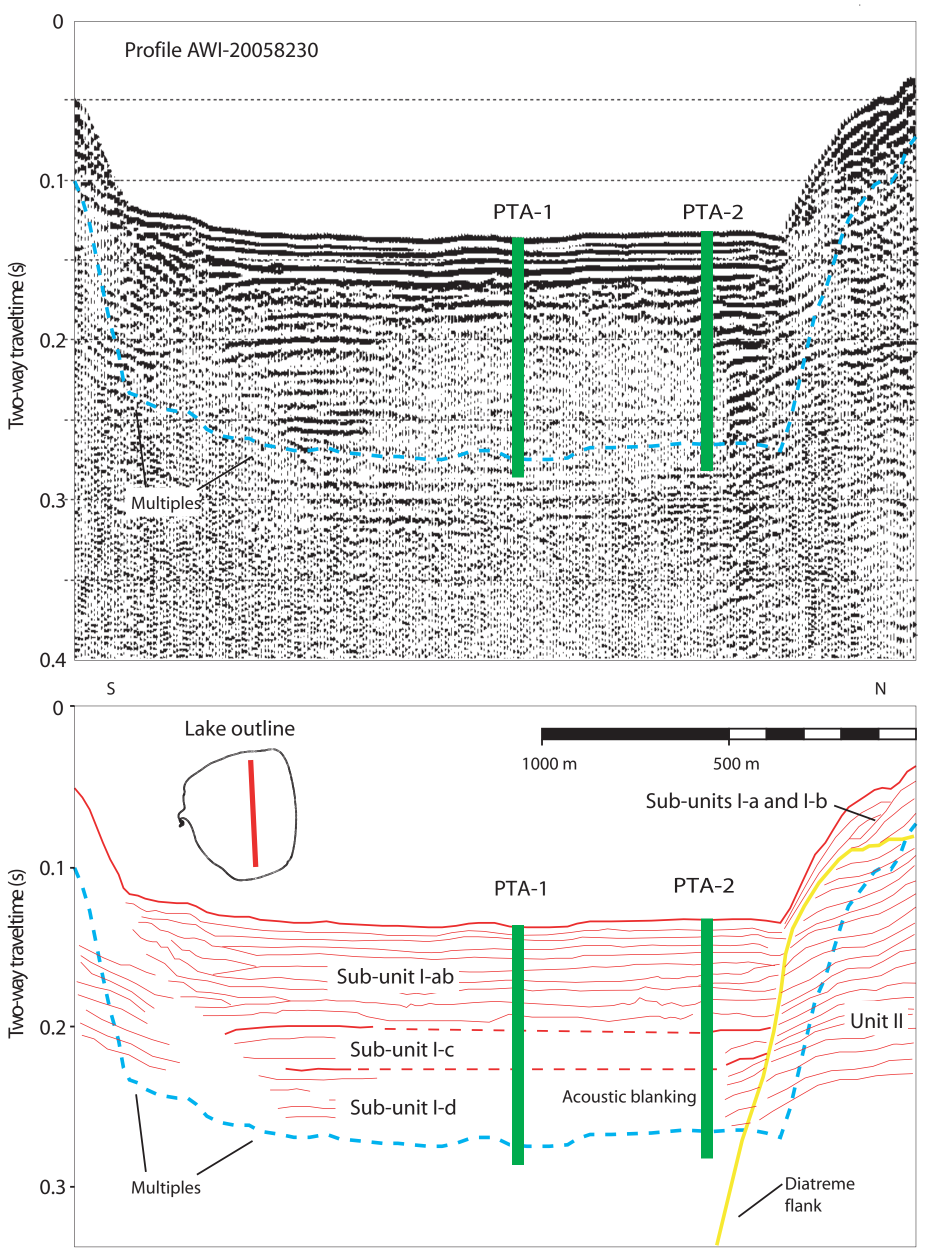

Figure 2. S-N multi-channel seismic reflection profile from Laguna Potrok Aike with uninterpreted seismic section (top) and interpreted line drawing (bottom). Drill sites PTA-1 and PTA-2 are marked. Inset (top left) shows outline of Laguna Potrok Aike with multi-channel seismic line (red) from Fig. 1.

Rainfall within the catchment area of Laguna Potrok Aike is highly variable and is mainly related to northward and southward shifts of the Southern Hemispheric Westerlies. A west wind belt over Southern Patagonia causes drier conditions (lee effect of the Andes), while a northward migration of the Westerlies allows rain-bringing easterly winds to introduce precipitation from the Atlantic Ocean (Haberzettl et al., 2007b; Mayr et al., 2007). Therefore, a paleorecord from this site has a large potential to act as a cornerstone for paleodata—climate model intercomparison (Meyer and Wagner, 2008; Wagner et al., 2007). It makes the water budget extremely susceptible to the regional precipitation-evaporation balance. In addition, a multitude of surficial and subaquatic lake level terraces can be found. A continuous 16,000-year record with high temporal resolution and a low-resolution 53,000-year record exist for Laguna Potrok Aike (Anselmetti et al., 2009; Haberzettl et al., 2007a, 2008; Mayr et al., 2007, 2009; Wille et al., 2007).

Objectives, Project Planning and Drilling Operations

The recent discovery of an exceptionally thick (~400 m) sediment sequence for Laguna Potrok Aike (Anselmetti et al., 2009; Gebhardt et al., 2009) has sparked an international research effort directed towards an interlinked approach that addresses two key objectives: (1) the evolution of maar craters and (2) quantitative climatic and environmental reconstruction.

Recovery of more than 400 m of sediments from a water depth of 100 m requires rotary drilling. The goal of the PASADO (Potrok Aike maar lake Sediment Archive Drilling prOject) deep drilling project was to recover triplicate cores from two sites and one core from a third site with inclined drilling (sites 1–6 in Fig. 1). The anticipated target depth ranged from 50 m to 600 m blf (below lake floor). Drill sites 2 and 5 (Fig. 1) had highest priority where seismic data indicated the potential for a penetration down to at least 400 m blf within the center of the basin, where hiatuses related to lake level fluctuations are less likely to exist (Fig. 2). Penetration was also planned into the volcaniclastic deposits below the 400 m or more of lake sediments. The second drilling target is located on the circum-lacustrine lake level terrace at 35 m water depth (sites 1 and 4 in Fig. 1). An erosional hiatus was detected there (Haberzettl et al., 2008). It is anticipated that this discontinuous record and the record from the lake center would jointly provide information about hydrological variations. The inclined drilling site is located near the northern end of the lake at 90 m water depth (sites 3 and 6 in Fig. 1) where a deviated hole was intended to be drilled through the crater wall and into basement rocks to investigate the transition zone formed during maar eruptions.

Drilling operations took place from September 2008 to November 2008. Prior to drilling, many logistical and technical challenges had to be overcome. The main obstacle was the lack of harbor facilities as well as the inaccessibility of the lake shore for a crane. Thus, the drilling platform had to be launched in a unique manner with a specially designed carriage called the “Launcher”. This device made it possible to assemble the platform, including the drill rig and other heavy parts of equipment, on land and then lower the assembled barge downhill across the lake level terraces into a water depth sufficient to reach flotation. From the floating platform, drilling was carried out with the GLAD800 coring system operated by the Consortium for Drilling, Observation and Sampling of the Earth’s Continental Crust (DOSECC) (Fig. 3). However, due to weather-related and technical downtime, only one of the primary sites (site 2, PTA-1) was drilled in quadruplicate and one additional site in the deep center of the lake (site 7, PTA-2) was drilled in triplicate. These sustained an average core recovery of 92.1% (PTA-1) and 98.8% (PTA-2) (Table 1; Fig. 1). A total of 533 m of cores were obtained reaching a maximum depth of 101.5 m blf at the deepest hole (PTA-2C). Almost all coring was done with the Hydraulic Piston Corer (HPC), and one core run was drilled with the Extended Nose Corer (EXN). Rotary drilling was not applied because sediments at 100 m blf were still rather soft. The planned comprehensive downhole logging program combined with seismic experiments could not be conducted, due to the fact that all holes had to be abandoned in emergency because of unseasonably strong westerly winds.

Figure 3. Platform *R/V Kerry Kelts* with the GLAD800 drilling system (center).

In the field laboratory all cores were logged with the multi-sensor core logger (MSCL) provided by the ICDP. Magnetic susceptibility was obtained in 2-cm intervals for all cores. GRAPE (gamma ray attenuation porosity evaluation) density was not operational because we were not allowed to import the gamma ray source into Argentina. P-wave velocity measurements did not provide any signal, probably because the coupling between inner liner wall and sediment was imperfect. All core catcher samples were studied in the field laboratory for their physical and chemical properties including pH, Cl^{-}, Ca^{2+}, electrical conductivity, water content, and dry density. Additionally, an initial lithologic description was carried out consisting of digital photography and macroscopic as well as microscopic description,(using smear slides for the latter). In addition, biotic activities related to early diagenetic processes were investigated as follows. This “deep biosphere” research tracks microbial activity through depth (Amend and Teske, 2005). On-site analyses included the detection of living organisms using ATP (adenosine triphosphate) measurements accompanied by sampling under the most sterile conditions possible. Immediate chemical fixation of the samples secured the best preservation of natural conditions for further laboratory studies. Sediment cores were then stored in a refrigerated container shipped to the GEOPOLAR Lake Core Repository at the University of Bremen where core splitting, scanning, and subsampling takes place.

Table 1. Location of drill sites, water and penetration depths as well as core recovery rate

Site	Latitude (Deg.S)	Longtitude (Deg.W)	Water Depth (m)	Penetration Depth (m blf)				Average Recovery
				Hole A	Hole B	Hole C	Hole D	
PTA-1	51.96403	70.37595	98	88.1	71	62.3	100.4	92.1
PTA-2	51.97053	70.37551	95	88.5	21.1	101.5		98.8

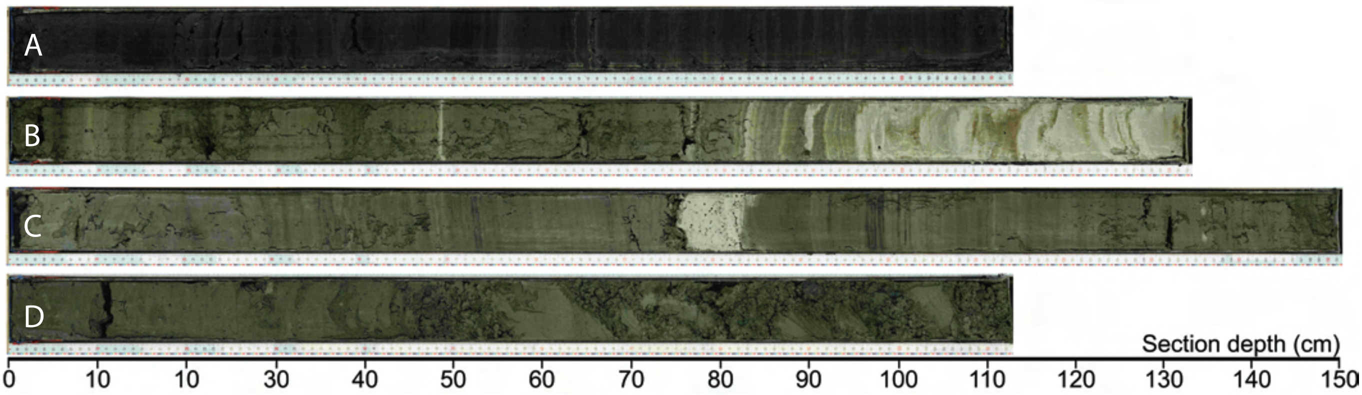

Figure 4. Selected split core sections from site PTA-2 (5022-2A). From top to bottom these represent [A] Holocene dark gray, laminated and carbonaceous silts starting from 6.39 m blf; [B] clastic and volcaniclastic, greenish-gray laminated and carbonaceous silts from 13.52 m blf; [C] clastic and volcaniclastic, greenish-gray laminated silts from 28.54 m blf; [D] clastic, greenish-gray sand and gravel from 82.52 m blf.

Preliminary Results

During the ICDP field work we recovered the longest environmental and climatic record (so far) for South America south of the tropics. However, lacustrine deposits were not penetrated completely, and volcaniclastic sediments were not reached. The total catch of cores was only 29% of what was proposed; thus, one of the two objectives of PASADO—the study of the basal volcaniclastic sediments—was not addressed.

All cored holes were correlated by applying MSCL (magnetic susceptibility core logger) data. The longest (101.5 m) lacustrine record consists mainly of lacustrine mud. Despite this dominance, grain sizes vary considerably from layers of almost pure clay and sandy sections (especially below 50 m blf) to gravel beds (Fig. 4). Some of the latter are related to volcanic ash layers consisting of sands with coarser scoria components. Surprisingly enough, rounded gravels were also recovered from the center of Laguna Potrok Aike. This can only be explained by either drastic lake level lowering until fluvial activity reached the coring site or seasonal lake freezing during the last glacial with snowmelt-related slush flows deposited onto the ice cover and coarse particles relocated as drop stones. We favor the latter interpretation, because lake level lowering should cause precipitation of evaporates like they presently occur at Laguna Maar Bismarck, a modern analogue for such conditions in the Pali Aike Volcanic Field.

There is a clear Holocene signal in the core catcher data (Fig. 5). However, the presence of older interglacial (Eemian; Oxygen Isotope Stage = OIS 5.5) is missing within the recovered sections. This finding is consistent with linear extrapolation of the age model developed for piston cores of the last 16 ka (Haberzettl et al., 2007b), and it suggests an estimated age of ~85 ka for the lowermost sediment recovered. Preliminary microfossil analyses of core catcher samples show a clear difference between Holocene and glacial conditions in the upper part of the profile, and reveal increases in diatom frequency and pollen of shrub taxa for the lowermost part of the profile. Based on these data, the obtained sediment record may extend back to OIS 5.1.

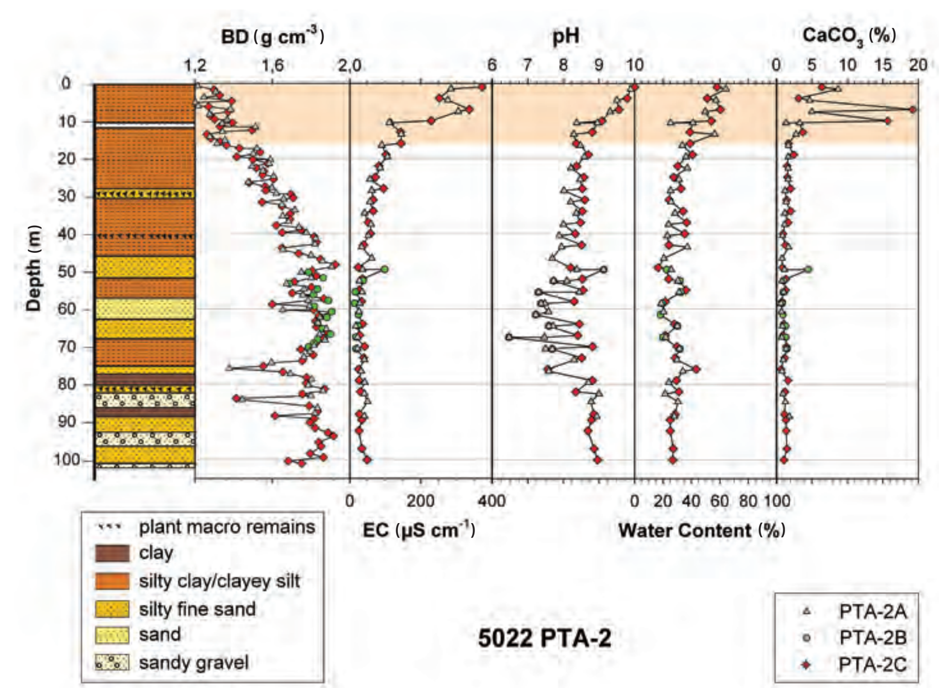

Figure 5. Lithostratigraphy and records of bulk density (BD), electrical conductivity (EC), pH, water content, and carbonate content ($CaCO_3$) based on core catcher samples from site PTA-2 (combined holes A, B, and C) as obtained in the field laboratory. The Holocene section of the record is shaded in an orange hue (top).

Summary

The 770-ka-old maar lake of Laguna Potrok Aike was the target of the international deep drilling project PASADO, carried out in the framework of the ICDP from September to November 2008. Although the project could not recover the entire lacustrine sediment infill and volcaniclastics due to unusually windy conditions and technical problems, PASADO drilled seven holes at two sites in the central deep lake basin to a maximum depth of 101.5 m blf. A total of 533 m of sediment cores was gathered with a mean recovery rate of 95.5%. Currently, sediments of this longest Patagonian lake record to date are subsampled and analyzed. First detailed scientific results are expected for the year 2010.

Acknowledgements

We are grateful to Beau Marshall and the DOSECC drilling crew as well as to Capitan Jorge Daniel Moreteau and his son Javier for their excellent technical skills. Without them the PASADO field work would not have been possible. We also thank the members of Instituto Nacional de Tecnología Agropecuaria (INTA) Santa Cruz, in particular Guillermo Clifton and Gabriel Oliva, for providing logistical support and the ground for the field camp at their experimental field station Potrok Aike. Many thanks go as well to Cristobal Zimmermann of the German Embassy in Buenos Aires. Without his steady support many customs affairs would have been unsolvable for us.

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Bio-Archive Core Storage and Subsampling Procedure for Subseafloor Molecular Biological Research

by Noriaki Masui, Yuki Morono, and Fumio Inagaki

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Introduction

The Integrated Ocean Drilling Program (IODP) provides unprecedented opportunities to study the deep subseafloor biosphere. Subseafloor microbes play important roles in biogeochemical cycling of carbon, nitrogen, sulfur, metals, and other elements on geologic timescales; however, their growth and metabolic characteristics remain largely unknown because most subseafloor microbes are phylogenetically distinct from known isolates and resistant to culturing in laboratories. Given the significance of this region as potential habitats of subseafloor life, cored materials (or portions thereof) should be frozen in long-term storage to provide opportunities for future molecular analyses arising from rapid biotechnological developments (D'Hondt et al., 2007). Here we report a semi-aseptic subsampling technique for frozen core samples using an electric saw system in a clean booth. This subsampling technique enables us to share and distribute samples from the same depth for multiple analyses, such as DNA and lipid biomarkers, without thawing the frozen core.

Problems with Current Storage Conditions

The activity of subseafloor microbial life is generally very slow (D'Hondt et al., 2002, 2004); however, it impacts biogeochemical cycling on Earth on geological timescales, and moreover it provides clues for understanding the origin and evolution of life. Microscopic observations as well as molecular (e.g., DNA) surveys demonstrate widespread microbial presence in the marine subsurface environment (Parkes et al., 1994, 2000; Inagaki et al., 2006; Lipp et al., 2008; Morono et al., 2009). Given the significance of cored materials for studying deep subseafloor life and the biosphere, legacy samples called "Bio-archives" are extremely useful for studying distributions of biomass, diversity, community composition, habitability, and metabolic activity. To achieve bio-archive storage and sample distribution, new sampling techniques are in high demand to minimize damage and contamination.

During the long history of scientific drilling, most cores have been stored at room temperature or around 4°C in open storage rooms. However, contaminating microbes from the air or scientists themselves easily grew under these storage conditions (Fig. 1) and thus caused critical damage to core quality. Oxygen penetration stimulates growth of contaminating aerobic bacteria as well as germination of buried fungal and bacterial spores. Since aerobic bacteria grow on organic matter in cored sediments, the dramatic change in conditions during storage easily kills subseafloor microbial life. After cell death, fragile bio-molecules such as RNA, enzymes, sugar chains, and intact polar lipids rapidly degrade via abiotic hydrolysis and enzymatic reactions, subsequently promoting the activity of contaminating microbes. In addition to preventing such degradation, freezing cores also prevents dissolution of carbonates during long-term storage and hence maintains the fine textures of carbonate fossils. Therefore, preserving frozen core materials under appropriate conditions is necessary for microbiological and biogeochemical studies.

Electric Band Saw System

During previous ODP/IODP expeditions, most microbiological samples were obtained as whole round cores (WRC) and stored at -80°C. One of the difficulties of frozen WRC handling is subsampling for molecular biological or biogeochemical analyses in shore-based laboratories. In the past, to collect subsamples from a frozen WRC, cores were thawed on a clean bench, then an innermost sample was collected using a heat-sterilized spatula or an autoclaved tip-cut syringe, and the rest of the sample was returned to the deep freezer for subsequent analyses. This freeze-thaw cycle enhanced damage of endolithic and sedimentary bio-molecules and increased the probability of experimental contamination. Alternatively, frozen cores could be manually broken with a heat-sterilized chisel without the risk of melting; however, collecting the innermost part of the core that had avoided

Figure 1. An example of contaminating microbial colonies growing on the core surface after long-term storage (ID: 190-1174B-63R-3W). Bar indicates 1 cm.

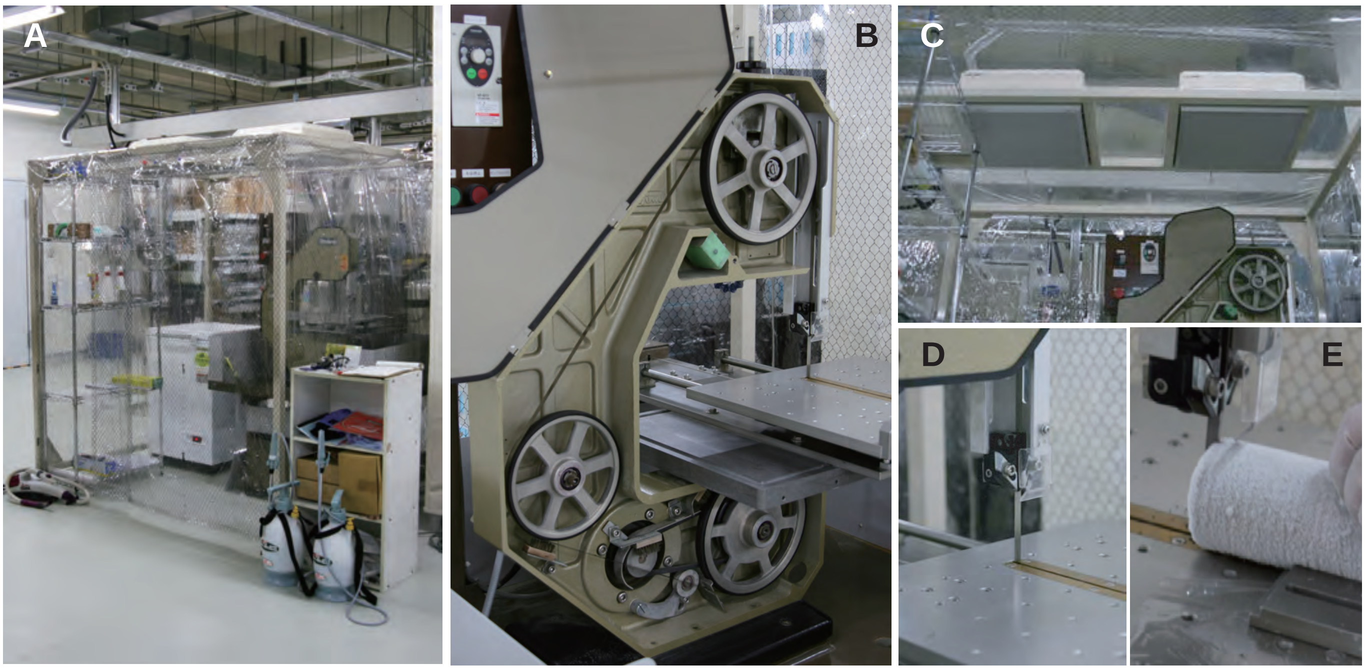

Figure 2. [A]Overview of the electric band saw system for microbiological frozen core. Motor-driven electric band saw machine [B] and -50°C freezer is deployed in a clean booth equipped with two HEPA-filter units [C]. Diamond-tipped band saw cuts frozen core samples under clean conditions [D, E].

potential drilling fluid contamination was difficult.

For better analytical use of frozen WRC and other types of frozen geological materials such as rocks and sediments, we constructed a semi-aseptic electric band saw system. A diamond powder-etched band saw machine (RYOWA Co. Ltd., Japan) and a -50°C freezer for temporary core storage were set up in a clean booth equipped with two HEPA-filter units (Model ATML-2-E252, NIPPON MUKI Co. Ltd., Japan) (Fig. 2). The electric saw smoothly cuts frozen WRCs under clean air in a short time without melting the core. In standard applications, the electric band saw is cooled with water to prevent frictional heat buildup; however, this step is not necessary for frozen cores, which are even better for maintaining aseptic conditions. Cutting the frozen core also eases multiple rounds of subsampling without disturbing the stratigraphic conditions. To prevent cross-contamination, it is necessary to clean the saw's parts, such as the saw blade and its wheels, using a steam-heat cleaner (Fig. 3) followed by an ethanol spray and a Milli-Q water rinse.

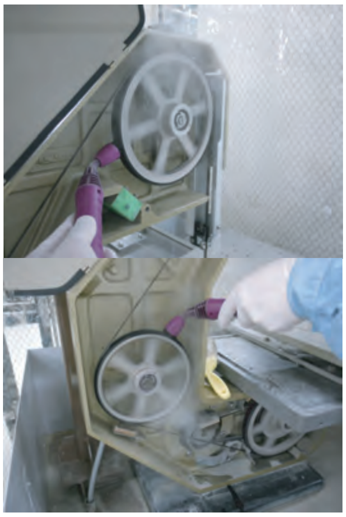

Figure 3. Cleaning run. Band saw and three wheels must first be cleaned with heat-steam followed by an ethanol spray-wash and a Milli-Q rinse.

Example of Frozen Whole Round Core Subsampling Possibilities

The electric saw system described herein enables quick subsampling of frozen cores into various shapes. For examples, the frozen WRC is first cut in half vertically, and one of the halves is cut into a plate shape (Fig. 4). Then the plate can be cut into bars (5 mm x 10 mm). A 6.5-cm-diameter core, which is the usual ODP/IODP core size, yields forty-six of these subsampled bars. As many of the frozen bar samples as needed can be used for molecular analyses. For experiments requiring larger volumes, half of the WRC may be used. Overall, this protocol is flexible with respect to subsample volume, and it eases sharing the exact same horizon among multiple analyses.

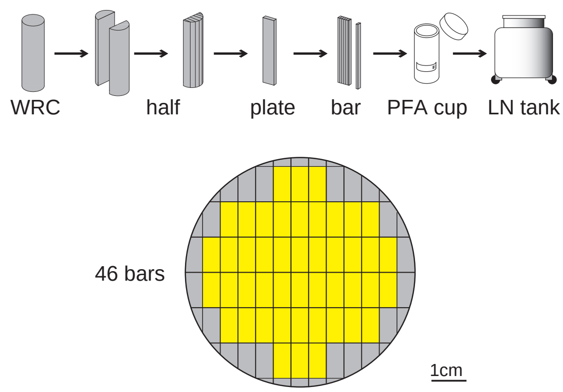

Figure 4. An example of frozen whole round core (WRC) subsampling. The WRC is first cut in half lengthwise, then one half is sectioned into plates, and each plate is cut into bars. Cut core samples are put in PFA cups and stored in a liquid nitrogen tank at -160°C (or deep freezer at -80°C).

Storage of Frozen Bioarchives

For optimal preservation, the initial freezing step is important. Flash freezing with liquid nitrogen (LN) is better than normal (slow) freezing. Cores should then ideally be subsampled with the electric saw system and stored either in a LN tank or -80°C deep freezer until examined. For effective preservation of RNA, the sample should be put into a commercial RNA-stabilizing solution (e.g., RNAlater®, Ambion), the supernatant removed after several hours' incubation at 4°C, and then the sample put into the deep freezer. RNAlater®-ICE (Ambion) may be useful for recovering RNA from frozen samples during thawing. Sample preservation in acetone may be an alternative method to preserve RNA (Fukatsu, 1999).

For long-term storage we are currently performing trials using a LN tank (Fig. 3), whose (gas phase) temperature is approximately -160°C (T liquid phase = -196°C) . It is well recognized that lower temperatures are better for long-term storage of fragile biomolecules, and an oxygen-free nitrogen atmosphere is suitable for preserving oxygen-sensitive enzymes and anaerobic microbes. For samples stored in a LN tank, a cup made of PFA (perfluoroalkoxylalkane) is the best choice despite its price, because PFA withstands temperatures ranging from -196°C to 200°C and hence is also autoclavable. PFA cups are also useful for storing methane hydrate samples; liquid nitrogen can be poured directly on the samples in a cup. These options should be practiced onboard in order to preserve biological samples most effectively.

Future Developments

Several possibilities are conceivable for future uses of bioarchived cores. First, if this electric saw system can be deployed on drilling platforms, frozen samples at the same horizons can be distributed among researchers, and the rest can be returned for sedimentological and paleontological studies or standard archiving. This process will minimize sample volume and avoid sample location differences among multiple analyses; however, we need to modify the system for ease of use, smaller sample sizes, and reduced costs. The cleaning step must be modified to save time and to simplify its execution. In addition, we are currently testing an improved mini-core sampling system using an autoclavable metal tube with a saw tip, which allows onboard subsampling not only of frozen samples but also of hard rocks.

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"Core on deck!" The End of SODV and the Return of the *JOIDES Resolution* as the IODP Riserless Vessel

by Peggy Delaney and Sean Higgins

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In February 2009, after a 3-year operational hiatus in order to undergo a major retrofit, the *JOIDES Resolution* (or simply the *JR*, as it has been called since 1985) reverberated with the trademark phrase, "Core on deck!". For the crew and technical staff aboard during the *JR*'s sea trials cruise in January–February 2009, it brought shouts of joy and tears of relief from years of rebuilding the *JR* in a Singapore shipyard, and a realization that we were "really" going back to carrying out international expeditions. But what does the phrase mean to marine geoscientists around the world? For most scientists, it means that one of the only tools to explore sediments and rocks in the deep sub-seafloor throughout the world's oceans is finally available again. This unique research facility is our community's equivalent to the Hubble telescope and provides the access we need to the deep ocean. Accumulating an impressive array of accomplishments, the *JR* (Fig. 1) has served as the sole scientific drilling vessel for the Ocean Drilling Program (ODP, 1985–2003) and for the initial phase of riserless drilling for the Integrated Ocean Drilling Program (IODP, 2003–2006). Over 120 expeditions since 1985 have retrieved samples encompassing a latitudinal range from 80.5°N to 70.8°S, a water depth range from 85 m to nearly 6000 m, sub-bottom depths as deep as 2.1 km, and a total depth range (water depth plus penetration) over 6.9 km.

As part of the United States' contribution to IODP, the National Science Foundation—through Geosciences Directorate and through its Major Research Equipment and Facilities Construction (MREFC) Account—provided more than $100 million in funding for the conversion and upgrade of the *JR* after it was selected in a public competition. This project, known by the acronym "SODV" (Scientific Ocean Drilling Vessel), has been an extended journey for those involved in bringing the *JR* back to life, unlike any project any of us could have imagined when it started out in the spring of 2006. Following on the heels of Hurricane Katrina and a worldwide boom in oil prices that led to the biggest shipbuilding boom in oil industry history, rebuilding the *JR* could not have faced a more complex set of obstacles. Delivery of SODV came in January 2009, more than a year later than we had planned and only after near-heroic efforts from both the Transocean and Overseas Drilling Limited ship's crew and technical staff from the U.S. Implementing Organization (USIO) (Texas A & M, Lamont Doherty Earth Observatory's Borehole Research Group and the Consortium for Ocean Leadership). The management of all these organizations also played a critical role in pushing for and accomplishing the SODV project.

Figure 1. The pre-modernized *JOIDES Resolution*, an ~143-m-long, dynamically positioned drill ship, with a derrick extending >61 m above the water line, began operations in 1978 as the *SEDCO/BP 471* and was converted in 1985 for use by the Ocean Drilling Program (ODP). The derrick height and overall size allow this vessel to be able to access a wide variety of ports, including passing under the Bridge of the Americas (Panama) and the Golden Gate Bridge (San Francisco, California). The name came from the JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) advisory structure and after the *HMS Resolution*, the vessel of exploration commanded by Captain James Cook. By the end of ODP and during initial IODP operations, the *JOIDES Resolution* (*JR*) included a fully equipped lab stack, the scientific heart of expeditions, equivalent in its fitting and capabilities to shore-based research laboratories.

The SODV project has its roots in a decade-long process of imagining the next many years of scientific ocean drilling

Figure 2. The Core Deck labs are but a portion of the all-new and larger lab facilities. The scientific equipment and systems in the labs were newly acquired, upgraded, or refurbished, based on experience gained in past expeditions and consultation with the international scientific advisory structure of IODP.

and translating this vision into a reality that guided the teams responsible for the conversion of a riserless drilling vessel for use by IODP. Recollecting the events, this all started in the Conceptual Design Committee (CDC) Report (2000) or the international Conference on Multi-Platform Exploration of the Ocean (COMPLEX) report in 1999 and, finally, the summarized requirements for a new riserless vessel in the USIO's Briefing Book (2005). This conversion project was guided by several overarching priorities (e.g. to provide more reliable riserless drilling vessel; to meet or exceed modern health and safety requirements; and science, sampling, and logging capabilities along with operational efficiency) and by a structure built to ensure science community input at multiple levels. One of the areas of greatest importance is preserving and enhancing the drilling, coring, sampling, and logging capabilities within the financial and physical limitations of the program. The project was focused on reliable, cost- and time-efficient drilling rig operations. Central goals were core quality and core recovery, including the ability to make holes with good progress in difficult lithologies where great depths must be achieved, and the ability to deploy the widest variety of downhole logging instruments and sampling tools.

In March 2009, the refurbished *JR* arrived in Honolulu harbor on an unusually crisp morning after six weeks of sea trials that took the ship on a >6000-mile odyssey from an emotional departure in Singapore to Guam to the Ontong Java Plateau and finally to Hawaii. After the *JR* just gained access to the science laboratory spaces in late November 2008, installation of over sixty instruments, an entire IT infrastructure, and more than 100 new software applications was completed, thus readying the *JR* (or nearly so) for its first science party since the end of 2005 (Fig. 2). This expedition (320T) was an intense testing period by both USIO staff and community participants, the Readiness Assessment Team (RAT) who produced an important baseline readiness report that documented current lab status and priority items that still needed attention. But, perhaps more importantly, the ship itself, the life supporting vessel systems, its critical drilling systems, newly refurbished derrick and passive heave systems, and new downhole logging system were also tested. After the ship had been guttee from the derrick forward, the *JR* was indeed alive and kicking. All conversion and capabilities of the *JR* are listed at http://www.oceanleadership.org/programs-and-partnerships/ship-conversion/ and some examples are given below:

Examples of ship conversion:

- 34% increase in laboratory spaces (includes offices and conference space)
- Redesigned laboratory layout for better core handling and workflow
- Streamlined accessibility between laboratories and accommodations areas
- Enclosed, sound controlled core splitting and sampling room
- Improved core flow and integration of science activities on the Core Deck
- Refrigerated core storage for >8000 m of core
- New ergonomic core description stations and software
- New and enhanced laboratories
- Refurbished sub-sea camera system
- Improved core handling capability
- New and expanded data servers and storage systems
- Refined and expanded berthing
- Updated safety and environmental systems

As of the start of Expedition 320 in March 2009 (the first of two expeditions focused on studying Cenozoic climate history of the equatorial Pacific), we no longer have to imagine what it might be like on the riserless scientific ocean drilling ship for the IODP in 2009 and beyond. Based on the many tours given in the first two port calls, scientists wondering if the *JR* would really be different have seen the remarkable transformation of the ship, from the ship's new core (Fig.2), chemistry/biology, and downhole labs, to the light-filled galley on the main dec, to the all new integrated living quarters and the impressive new bridge (http://iodp.tamu.edu/labs/ship.html).

Ultimately, the true test of the *JR* is its ability to obtain quality cores and geophysical logs in a variety of environments. Expeditions 320 and 321 immediately put the drilling systems, pipe handling, and coring systems to work in over 5 km of water in the central Pacific Ocean. The refurbished passive heave system, new wireline heave compensator, and a new rig instrumentation system to capture details of ship's drilling performance will all be put to the test in our upcoming expeditions (see back cover). The *JR* has been retrofitted with modern technology and laboratories. In the coming years as it sails the world's oceans, it will again try to live up to its heritage (named after Captain Cook's *HMS Resolution*). The scientific progress that IODP is able to achieve with the *JR* is now up to a new generation of marine scientists.

Hawaiian blessing of ship in May 2009 port call in Honolulu. From left to right: Kahu Kordel Kekoa (Chaplain for Kamehameha Schools Kapâlama), Arden Bement (Director of NSF), Bob Gagosian (President, Consortium for Ocean Leadership), Brian Taylor (Dean of SOEST, University of Hawaii), Bjorn Kjerfve (Dean of Geosciences, Texas A&M Unviersity.

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http://iodp.tamu.edu/labs/ship.html
Ship Conversion and Capabilities: http://www.oceanleadership.org/programs-and-partnerships/ship-conversion/ship-conversion-and-capabilities/

The U-tube: A New Paradigm for Borehole Fluid Sampling

by Barry Freifeld

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Introduction

Fluid samples from deep boreholes can provide insights into subsurface physical, chemical, and biological conditions. Recovery of intact, minimally altered aliquots of subsurface fluids is required for analysis of aqueous chemistry, isotopic composition, and dissolved gases, and for microbial community characterization. Unfortunately, for many reasons, collecting geofluids poses a number of challenges, from formation contamination by drilling to maintaining integrity during recovery from depths. Not only are there substantial engineering issues in retrieval of a representative sample, but there is often the practical reality that fluid sampling is just one of many activities planned for deep boreholes. The U-tube geochemical sampling system presents a new paradigm for deep borehole fluid sampling. Because the system is small, its ability to integrate with other measurement systems and technologies opens up numerous possibilities for multifunctional integrated wellbore completions. To date, the U-tube has been successfully deployed at four different field sites, each with a different deployment modality, at depths from 260 m to 2 km. While the U-tube has proven to be highly versatile, these installations have resulted in data that provide additional insights for improving future U-tube deployments.

Figure 1. Schematic layout of the U-tube sampling system as deployed at the Frio Site, Dayton, Texas.

The U-Tube

The U-tube sampler is a simple positive fluid displacement pump which uses a high pressure gas drive. Wood (1973) demonstrated this methodology for shallow vadoze zone sampling using a porous cup inlet. Figure 1 shows a schematic of the U-tube sampler as configured for installation beneath a wellbore packer. The heart of the U-tube is the ball check-valve, which contains the only moving part of the sampling system in the borehole. A loop of tubing that terminates at the surface forms the "U". The check-valve is located beneath a "tee" at the base of the U and it permits fluid to enter the loop but closes (by application of gas from the surface) when pressure in the U is increased above hydrostatic. A sintered stainless steel filter terminates the inlet beneath the check-valve to prevent the check-valve from plugging.

To collect a sample, the U is first filled by venting the sample and drive legs to the atmosphere, thus allowing fluid to rise to the formation hydrostatic level. The sample is recovered by supplying high-pressure N_2 (or another inert gas) to the drive leg, closing the check-valve, and forcing fluid out of the sample leg. While conceptually the U-tube is straightforward, the ability to independently control pressures on both the drive and sample legs presents numerous options for collecting and processing of fluids at the surface. By repeating sample collection cycles, the borehole fluid can be flushed and fresh fluid pulled in from the formation. The volume of the sample depends on the formation pressure as well as the diameter and wall thickness of the tubing used, but for an installation at a depth of 1 km, a 6 mm or 9 mm diameter tube with a 1.2 mm wall thickness has a U-tube volume of 20 L or 68 L, respectively.

The Frio Brine Pilot—CO_2 Storage and Multiphase Fluids

The Frio Brine Pilot was the first deep borehole application in which I deployed a positive displacement pump incorporating small diameter tubing and a check-valve. The Frio Brine Pilot, Dayton, Texas, was a demonstration program for the geosequestration of CO_2 in saline aquifers led by the Texas Bureau of Economic Geology (Hovorka et al., 2006). In September 2004, 1600 t of CO_2 were injected into the Frio Sandstone at a depth of 1.5 km over a span of ten days. A second experiment conducted in 2006 at the same site consisted of an injection of 350 t of CO_2 in sand at a depth of 1.6 km. The objectives of the Frio Brine Pilot tests included understanding the hydrological and geochemical impact of the CO_2 on the subsurface and evaluation of various monitoring tools that would inform us as to the shape and distribution of the CO_2 plume. In addition to surface and cross-hole seismic monitoring, we used fluid sampling from an observation well placed 30 m up-dip from an injector well to determine changes in the geochemistry as the plume swept past, and interpret the arrival of added tracers.

The constraints on the fluid sampling program were many. We had to do the following:

- Minimize impact on the flow-field
- Permit wireline logging operations
- Coexist with other downhole sensors, which included a tubing deployed seismic source, a string of hydrophones, and a pressure/temperature sensor
- Conduct frequent (hourly) sampling
- Allow for on-site real-time analysis of pH, alkalinity, and gas composition
- Enable functioning in a water-only, gas/water, or gas-only system
- Accurately determine the ratio of supercritical CO_2 to formation brine in the sampled fluid

The standard sampling technologies that were considered and rejected included electrical submersible pumps (unable to operate in two-phase systems), wire-line deployed flow-through samplers (unable to operate at high frequency during a 24-hour-a-day, multi-week experiment), and gas lifting (it would be difficult to control the flow rate, and the large volumes produced would disturb the flow-field. It would also be difficult to interpret downhole gas chemistry because of the large volume of lifting gas.).

The Frio Brine Pilot U-tube design consisted of a loop of 3/8" × 0.049" wall 316 L stainless steel tubing, which at a depth of 1.5 km contains a volume of 118 L. Four 13 L high pressure stainless steel cylinders were used to store the sampled fluid on the surface for analysis. The U-tube control lines and other instruments were strapped onto production tubing using cable protectors (Cannon Services Ltd., Stafford, Texas, U.S.A.). To isolate the perforated interval in the 5½" casing, a pneumatic packer with feedthroughs to accommodate various lines was located at the base of 2⅞" production tubing. From a geochemical sampling standpoint, it would have been best to locate the bottom of the packer just above the top perforation, minimizing the volume below the packer. However, to accommodate logging operations, the packer was set 14.3 m above the top perforation. The inlet port to the U-tube—a sintered stainless cylinder (60 cm long × 19 mm diameter, 40 µm pore size; Mott Corporation, Farmington, Conn., U.S.A.)—was located 30 cm below the bottom of the packer. The volume of the cased interval between the bottom of the packer and the top of the perforations was 177 L, with the 6.1 m perforated interval having an additional 75.4 L volume. Every two cycles of the U-tube would purge a volume equal to the dead-space between the top of the perforated interval and the U-tube inlet.

In contrast to the simplicity of the downhole U-tube system, the surface processing of the recovered fluids was quite complex. The U-tube surface completion consisted of six different manifold assemblies, allowing for careful control of sampling conditions and complete system purging between samplings. To facilitate reproducible sampling and minimize the potential for operator error, the sampling operation was automated with pneumatically operated valves. Control software was developed using the graphical programming language Labview (National Instruments, Austin, Texas, U.S.A.). Figure 2A shows the four 13 L sample vessels along with associated valving and gauges, with strain gauges mounted at the base of each cylinder to measure the bulk

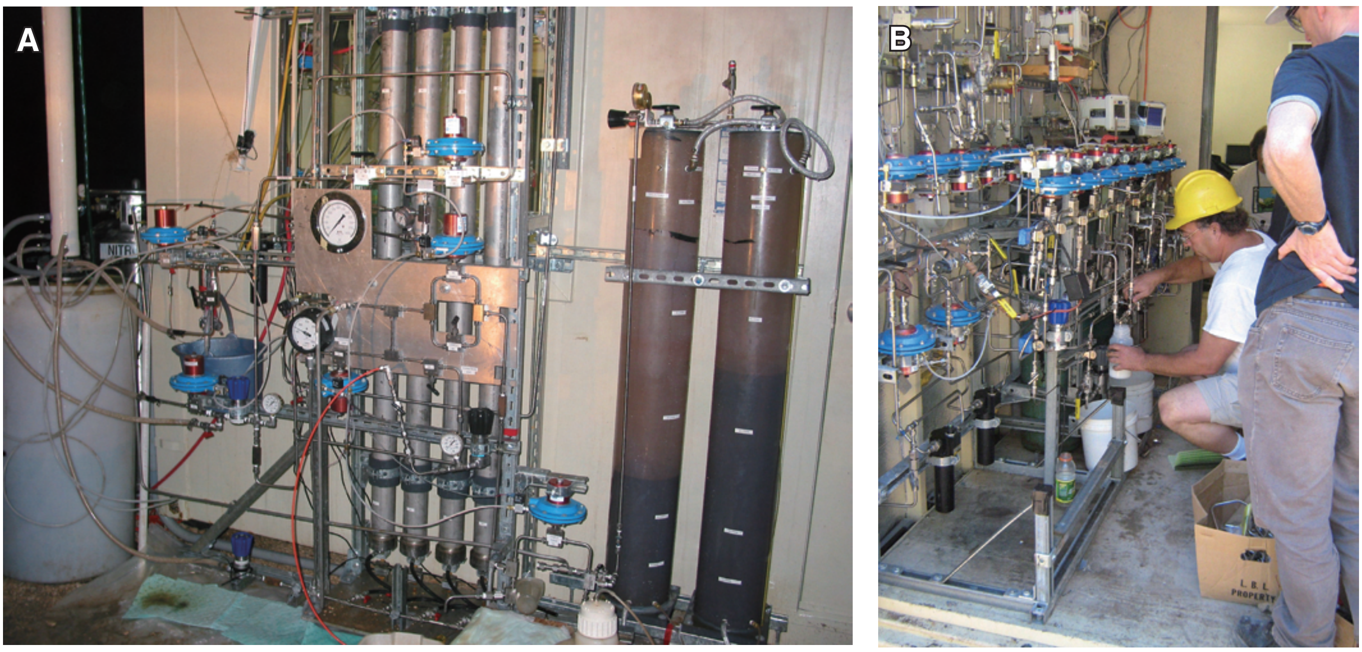

Figure 2. The Frio Brine Pilot surface sampling systems: [A] Four 13 L high pressure sample vessels mounted in sliding sleeves and resting on strain gauges to measure fluid density. [B] Computer-operated valve manifolds used to operate the U-tube samplers.

density of the sampled fluid. Figure 2B shows the bank of automated valves needed to operate the various manifolds. Lifting the water from the sampling interval to the ground surface via the U-tube and collecting and analyzing the samples involved an eight-step process described in detail in Freifeld et al. (2005). In short, the process consists of (1) filling the U-tube with borehole fluid by venting the drive and sample legs to the atmosphere; (2) purging the gas sample manifold, sample vessels, and liquid sample manifold with N_2 gas to remove any residual fluid from these systems prior to sampling; (3) bleeding down the N_2 to atmospheric pressure inside all of the process tubing and sample vessels; (4) evacuating the N_2 from the sample cylinders; and (5) charging the U-tube drive leg with N_2 to close the downhole check-valve and force fluid to the surface (steps 6–8 described below). The first 20–25 L of fluid produced from the sample leg was discarded because it was considered potentially phase-segregated. At the end of Step 5, bulk samples were collected from the sample leg in small, transportable high-pressure cylinders for later laboratory analysis, as well as in open containers for immediate on-site measurement of pH and alkalinity. Step (6) consisted of directing the sample fluid from the sample line into the evacuated high-pressure cylinders until a pressure gauge indicated that the cylinders were at formation pressure. The final two steps consisted of (7) directing a gas sample from the top of the sample cylinders to a quadrupole mass spectrometer (Omnistar, Pfeiffer Vacuum Technology, Nashua, N.H., U.S.A.) and (8) N_2 purging the remaining fluid from the U-tube, so that it could repeat the cycle for the next sample.

Some problems arose during the operation.

1. Hydrate formation and freezing occurred at some of the vent values because of Joule-Thompson cooling.
2. The large volumes of gases and high moisture and salt content bypassed various collection systems and disabled rotary vane and oil-based vacuum pumps.
3. The carefully developed automated sampling routines had to be modified as gas contents increased and system behavior changed.

In the end, it was learned that leaving the sample vessels filled with N_2 at one atmosphere both eliminated the complex evacuation cycle and facilitated the accurate estimation of dissolved gas concentration, by acting as a known reference standard (Freifeld and Trautz, 2006). The combination of limiting the pressure drop across vent valves and using heat lamps and heat trace tape stopped the formation of blockages in the system.

Despite considerable difficulty in keeping the complex system operating, forty-two aqueous samples were acquired over the first fifty-two hours of sampling, and rapid changes in geochemical conditions were observed as the CO_2 plume traversed the monitoring well (Kharaka et al., 2006). Figure 3 shows the gas composition for CO_2, O_2, Ar, and CH_4 measured

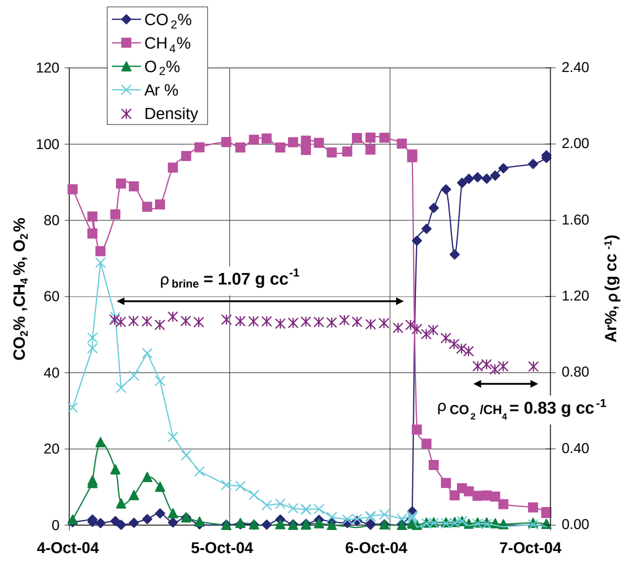

Figure 3. Frio Brine Pilot geofluid sample gas composition and density. Note that the presence of oxygen is indicative of atmospherically contaminated well-workover fluids.

on the quadrupole spectrometer, as well as sample fluid density. The presence of O_2 is an indicator of contamination with workover fluids that had equilibrated with air, and is not naturally found in the highly reducing environment of the Frio brine. Eventually, the sample streams changed from liquid to predominantly supercritical CO_2, and the self-lifting U-tube no longer needed compressed N_2 to drive the sample to the surface. While the system was self-lifting, the sample cylinders (based upon their known volume and measured pressure) were used to quantify the gas withdrawn from the ground and to estimate the time at which the gas entered the U-tube from the formation. The tracer travel times from the injection well to the U-tube sampler were used to estimate the formation CO_2 saturation. A geochemical interpretation of the rock-brine-CO_2 interaction has been presented by Kharaka et al. (2006), and a discussion on the quadrupole mass spectrometer methodology can be found in Freifeld and Trautz (2006).

Further Borehole Tests

A borehole in the Amargosa Valley (Yucca Mountain, Nevada) was drilled to a total depth of 400 m using a dual-wall reverse air rotary process to minimize subsurface contamination. The well was fitted with four U-tubes, two installed for permanent (redundant) use at two separate locations (264 mbgs and 348 mbgs), along with a distributed thermal perturbation sensor (DTPS) (Freifeld et al., 2008b). Sand and bentonite backfill materials were installed after lowering the instrument string in the open borehole strapped onto a 2" stainless steel piezometer (Fig. 4). Compressed gas cylinders of N_2 were used to operate the U-tubes. The initial produced fluid showed significant contamination with suspended bentonite, but after repeated operation, the fluid turbidity dropped. A single outlet valve on the N_2 cylinder

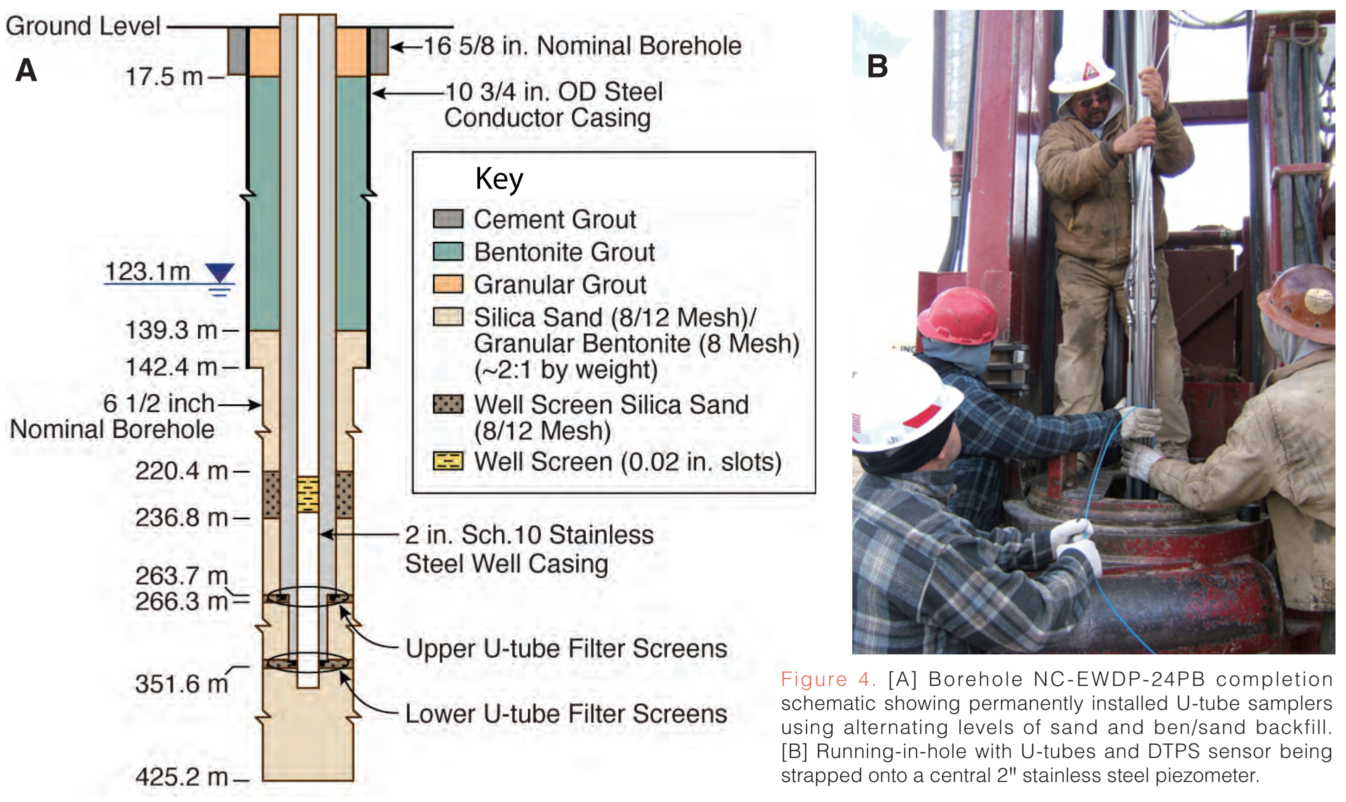

Figure 4. [A] Borehole NC-EWDP-24PB completion schematic showing permanently installed U-tube samplers using alternating levels of sand and ben/sand backfill. [B] Running-in-hole with U-tubes and DTPS sensor being strapped onto a central 2" stainless steel piezometer.

Figure 5. Multi-crane lift deployment of 32 m-long bottomhole assembly consisting of U-tubes, seismic sensors, and pressure temperature sensors at the CO2CRC Otway Project Site, Victoria, Australia.

pressure regulator controlled the flow of gas to the U-tube drive leg, and a separate valve was on the sample outlet.

The CO2CRC Otway Project (SW of Melbourne, Australia) is a program to demonstrate the storage of CO_2 in depleted natural gas formations (Sharma et al., 2007). The project drilled a well 300 m downdip of a depleted gas well to inject up to 100,000 t of CO_2 into the gas-bearing formation and monitor the previous gas well to assess geophysical and geochemical changes induced by injected gas.

The small-diameter casing (3½") posed the largest challenge to deploying a network of multilevel fluid sampling instruments. To instrument the well, a bottomhole-assembly (BHA) consisting of three U-tubes, two pressure-temperature sensors, and a string of seismic sensors was designed and fabricated. The entire BHA was lifted and installed as one 32 m-long assembly (Fig. 5) and lowered 2 km using conventional oil field sucker rod. The uppermost U-tube was installed near the top of the gas cap, while U-tube 2 and U-tube 3 were installed 1.5 m and 6 m below the gas-water contact, respectively. At the top of the BHA was a custom dual-element, double fixed-end packer. All three U-tubes have been functioning since their initial deployment in October 2007, with weekly sampling operations ongoing. The CO_2 injection caused the gas-water contact to be pushed down, and U-tube 2 and U-tube 3 have transitioned from sampling liquids to self-lifting and sampling predominantly gas. One significant hurdle overcome in the operation of the U-tubes was the unexpected presence of natural waxy alkanes in the fluids being produced (Boreham et al., 2008). As the wax traveled up the U-tube sample lines and cooled, it coated the U-tube lines, as evidenced by reduced flows, and eventually completely occluded the U-tube 1 sample line. The initial plug was dislodged using a high-pressure piston pump, and a solvent composed primarily of dialkyl- and trialkylbenzenes was used to eliminate future wax build up.

At the High Lake massive sulfide deposit in Nunuvut Territory, Canada, an existing boring was deepened for the purpose of characterizing sub-permafrost microbial communities. A borehole observatory consisting of a U-tube and pressure/temperature sensor was installed beneath a pneumatic packer. The borehole observatory was lowered by hand to a depth of 350 m, using the stainless steel U-tube and packer inflation lines as the strength member. By monitoring the pressure as the sample reservoir chamber filled, we estimated the formation hydraulic conductivity to be 2×10^{-11} m s^{-1} (Freifeld et al., 2008b). Despite heating of the borehole at 20 W m^{-1}, the presence of heavily mineralized zones (pyrite > 50%) along with temperatures of about -6°C led to the eventual freezing of fluid in the sample tubes. Seven samples were collected prior to the blockage of the tubes. This past summer a U-tube deployment below permafrost near Kangerlussuaq, Greenland used an insulating jacket around the sampling and heater lines to sucessfully prevent freezing while sampling.

Summary and Future Plans

The U-tube was successful in recovering fluid samples under diverse conditions from depths between 260 m and 2 km. In all four field deployments presented, the same downhole sampling equipment was used for fluid recovery, despite wide variations in deployment modality. Future plans for U-tube systems include deployments at CO_2 storage demonstration sites near Cranfield, Mississippi, at a depth of 3.1 km, along with an installation near Cholla, Arizona. Given the small, unobtrusive size of U-tubes, many other applications are possible, including in extreme environments such as in geothermal fields or subglacial lakes. The ability for U-tubes to provide minimally altered fluids and to be integrated with other measuring devices makes the U-tube an ideal choice for recovery of geofluids.

Acknowledgments

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Acquiring High to Ultra-High Resolution Geological Records of Past Climate Change by Scientific Drilling

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Introduction and Workshop Goals

Scientific drilling on land and sea has played a key role in advancing our knowledge of climate change. It has helped to demonstrate the effects of orbital variations on climate, revealed evidence for extreme warm events in the past and for the timing of Antarctic ice growth, and provided insights into the hydrologic balance of lake systems around the world. Now, with attention increasingly focused on the likely manifestation of future climate change, the challenge to understand past climates at societally relevant, high-resolution timescales has become ever more critical. Sediments and other archives that preserve climate information on timescales approaching those of instrumental records have much to offer to our understanding of how the climate system works (Fig. 1). These records, ideally with a sub-annual to centennial resolution, provide a unique opportunity to evaluate the global operation of the ocean-continent-atmosphere system on human timescales and to appraise the relative importance of each part of the system.

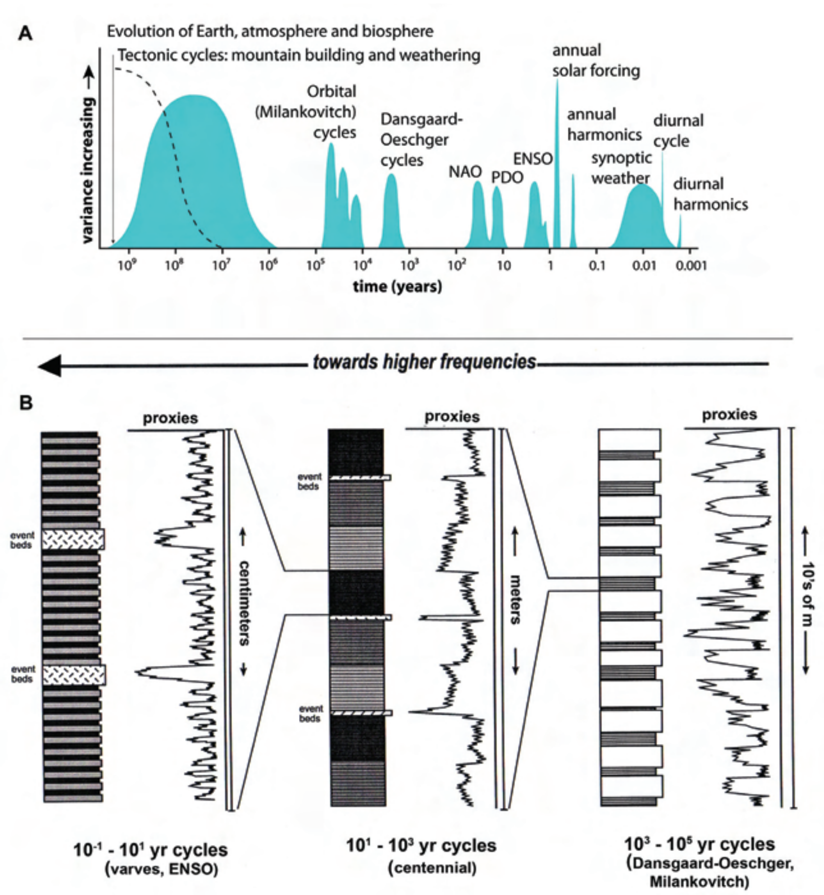

Figure 1. [A] The National Oceanic and Atmospheric Administration (NOAA) climate timeline http://www.ncdc.noaa.gov/paleo/ctl/ (the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO)). The resolution required of sedimentary records depends on the timescale of climate variability. [B] Different orders of climate cycles and their expression in sedimentary archives paralleled by changes in proxies. Higher frequency cycles are superimposed on the lower frequency cycles. The ability to resolve high frequency cycles (e.g., annual to centennial) in the geologic record is generally limited by the nature of the archive (i.e., whether they are sediments, corals, ice cores, or speleothems), the recording rate of that archive (dictated by sedimentation, growth, or accumulation rate), and the potential for post-formation disturbance (e.g., bioturbation in sediments).

Long high-resolution records of excellent quality acquired through ocean drilling have contributed significantly to our current understanding of climate (Ocean Drilling Program (ODP) Site 893, Santa Barbara Basin, California [Behl and Kennett, 1996; Hendy and Kennett, 2000]; ODP Site 1002, Cariaco Basin [Peterson et al., 2000; Hughen et al., 2004]). Comparable-resolution records recovered from lake drilling (Hodell et al., 2008; Scholz et al., 2007) and analyses of speleothems (Wang et al., 2001) have significantly enhanced the climate "portfolio" (Fig. 2). However, the existing inventory of high-resolution records generated by scientific coring and drilling in the oceans and on land (including ice) is currently limited in both number and global coverage (Voelker, 2002; Clement and Peterson, 2008). The acquisition and analysis of many more detailed multi-proxy records of past environmental conditions from all areas of Earth are needed to allow researchers to better understand why and how the climate system responds rapidly to external and internal forcing and how the various high-frequency oscillations of the climate system interact over longer time intervals.

A group of sixty-four international scientists—experts in the fields of marine, terrestrial, ice-cores and Earth-system modeling—met at the German Research Centre for Geosciences (GFZ), Potsdam, from 29 September through 1 October 2008, with the objective of identifying key climate questions best addressable with high- to ultra-high resolution records and designing scientific drilling strategies to recover them. The workshop was initiated and funded by the Integrated Ocean Drilling Program (IODP) and the International Continental Drilling Program (ICDP). Its primary aim was to find and/or explore key areas with potentially high-resolution records, in order to coordinate and integrate existing proposals from within IODP/ICDP and from other scientific programs and to develop new drilling proposals incorporating the objectives outlined in this workshop summary. The ultimate goal was to identify a global array of potential coring sites spanning different time intervals to fully understand the causes and consequences of rapid environmental/climate change.

The workshop opened with an invited series of keynote presentations designed to summarize our current understanding of climate change on sub-millennial timescales and to high-light recent advances and outstanding scientific issues. This was followed by talks that focused on the scientific missions, program structure, and proposal submission and review process for ICDP and IODP, and by short statements from all of the workshop participants about their research interests. A complete list of speakers and topics can be found on the workshop website (http://www.iodp.org/climate-ws-workshop/ Based on break-out group discussions, five overlapping climate themes emerged that are graphically represented by the petals of the flower diagram in Fig. 3. The interrelated petals are the main drivers of climate variability and, as such, form and inform the questions that can be addressed by high-resolution records. Within each of these themes, the nature and origin of abrupt climate change form a common thread.

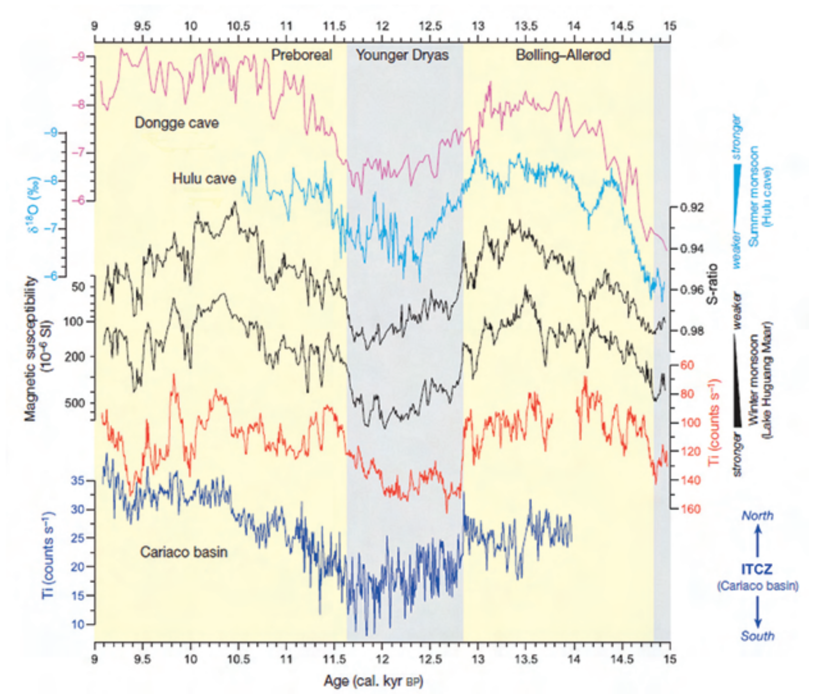

Figure 2. Comparison of selected high-resolution speleothem, lake, and marine records for the last deglaciation, with the well-known Younger Dryas cold event delineated by the gray bar (from Yancheva et al., 2007). Oxygen isotope records from Dongge and Hulu Cave stalagmites (China) are a proxy for rainfall and monsoon strength, as are the sediment proxy records (magnetic susceptibility, S-ratio, and titanium [Ti] counts) for Lake Huguang Maar in coastal China. Titanium abundance in sediments from Cariaco Basin, off northern Venezuela, is a proxy for regional rainfall and riverine delivery related to the changing position of the Intertropical Convergence Zone (ITCZ). These widely separated and hydrologically-sensitive records illustrate the potential for recovering high-resolution paleoclimate information from a variety of geologic archives.

Understanding the Causes and Consequences of Climate Variability

Climate Modes

High-resolution sedimentary archives from ocean and terrestrial systems provide a means of tracking climate variability throughout much of the globe at interannual to decadal to centennial/millennial timescales. They can be used to study past variability in the most important elements of the modern climate system, such as the El Niño-Southern Oscillation (ENSO), monsoons, the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO), and the Southern Annular Mode (SAM) (Fig. 1). Each of these modes or elements has been defined using instrumental climate and weather data, yet little is known about centers of action or centers of impact and about how these modes may have varied in the past under different boundary conditions.

Sedimentary archives can provide us not only with high fidelity records of past climate mode behavior—such as the millennial record of ENSO from its source region in the western Pacific (Tudhope et al., 2001)—but also with records of their teleconnected impacts around the globe (Wang et al., 2006). In this way, questions can be answered regarding the stationarity of ENSO-associated droughts or PDO-associated changes in North American temperature or snowfall (Mantua and Hare, 2002). Accordingly, the Potsdam Workshop identified as high priority for both IODP and ICDP the development of a series of climate mode reference sections

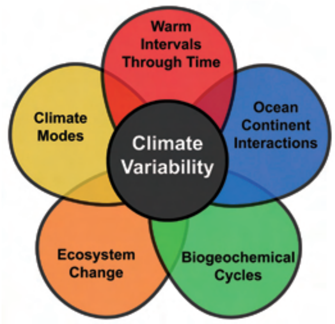

Figure 3. The five research themes shown here as "flower petals" emerged from workshop discussions as being central to the overarching goal of understanding the causes and consequences of climate change variability.

as well as response records from key parts of the globe. One suggestion was to focus on establishing the record of past variability in the global Walker Circulation (the zonal atmospheric overturning circulation that drives ENSO) as well as African and Asian monsoons. In the case of the Walker Circulation and ENSO, the acquisition of records that span the tropical Pacific from west (e.g., Papua New Guinea) to east (potentially Galapagos) should be a goal, as well as in regions that today show evidence of strong teleconnections, such as Ecuador, Peru, northeast Brazil, and South Africa. Combined with a similar latitudinal transect of high-resolution lake records from the western Americas, it should be possible to begin sorting out the relative forcing of ENSO as compared to such phenomena as latitudinal shifts in zonal circulation and changes in tropical convection.

During the last glacial period, the rapid temperature excursions over Greenland that have come to be known as Dansgaard-Oeschger events (Dansgaard et al., 1984, 1993) define a mode of climate variability that is critical to understand. The excursions appear to have a global imprint, though many regions are greatly undersampled (e.g., the Southern Hemisphere), and improved knowledge is needed of the spatial and temporal expression of these events. Their signature often seems to be manifested in variables other than temperature—for example, shifts in tropical rainfall patterns (Clement and Peterson, 2008). Abrupt, rapid climate change of this type, were it to occur in the future, could potentially put modern society under extreme stress. An urgent need exists to identify the 'symptoms'—the concatenation of events—that lead to the threshold of Earth's climate becoming markedly hotter or colder over the course of a decade or two. Paleoclimate records have revealed evidence of stressed ecosystems that are in disequilibrium during times of rapid climate change, with commonplace local extinctions. Future climate events have the potential to affect millions of people, most probably by disruption of the food chain or water supplies.

Geologic archives that preserve and can be sampled at high temporal resolution will help us answer questions about climate modes and abrupt change such as the following: What is the climate sensitivity to natural forcing, and how will anthropogenic actions influence this sensitivity? What changes might we expect in the Walker Circulation in the (warmer) years ahead? How variable can ENSO be? Is millennial variability present that shows ENSO patterns? What happened to ENSO during times of Pliocene warmth? Is there a real decadal mode in the Pacific? Is the PDO a distinct and separate element of the climate system? What is the role of the meridional overturning circulation (MOC) in the climate system on timescales ranging from decadal to millennial (Keenlyside et al., 2008; Stanford et al., 2006)? Is there a relation between the MOC and AO? Can sediment records be used to establish a definitive link between high latitude sea ice and the mean position of the Intertropical Convergence Zone (ITCZ) (Broecker, 2006)?

A number of strategies and data needs were identified to quantify conditions contributory to abrupt climate change in the late Quaternary. These include the development of proxies and drilling targets for reconstruction of sea-ice variability on various timescales; evaluating the sensitivity of ice sheets and sea level to past climate change to answer such questions as whether the West Antarctic Ice Sheet collapsed during previous interglacials; and examining whether inter-hemispheric phase-relationships known in the 100-kyr world were the same as earlier in the Pleistocene in the 41-kyr world.

Warm Intervals through Time

The most recent Intergovernmental Panel on Climate Change Report (IPCC, 2007) predicted that present and near-future global warming will produce boundary conditions very different from those of the last two million years; however, there is currently no clearly identifiable analogue for either the present interglacial or for anthropogenic climate warming. Models suggest that the Greenland Ice Sheet and perhaps portions of the West Antarctic Ice Sheet will begin to disappear as global climate warms (Gregory et al., 2004; Hu et al., 2009), but we don't really know if this happened previously within the warmest intervals of the late Quaternary. How sensitive were ice sheets (and sea level) to past climate change, especially during periods warmer than today (e.g., Marine Isotope Stages 5e, 11, 31)? What were the rates of change? Did the West Antarctic Ice Sheet collapse during previous interglacials?

Interglacial periods can be regarded as anomalies within the climate norm of the 100-kyr glacial cycles, which display the classic sawtooth pattern of abrupt beginnings that gradually subside towards the background norm (Fig. 4). Each interglacial is unique, and as such none can be used as a perfect analogue for the continued evolution of the present interglacial or for future climate change. One possible strategy is to compare all late Quaternary interglacials to generate 'an ideal interglacial' and a model for end-member states (Ruddiman, 2005). Re-examination of extant material and drilling a dedicated array of widely spaced high-resolution records are useful means of achieving this. Since oceans are buffers of climate change and lakes are amplifiers, transects of both marine and terrestrial records are prerequisites for achieving a complete picture of the patterns and magnitude of interglacial warmth.

Though it is natural to focus on recent interglacials because of the similarities in non-anthropogenic forcing, much can be learned from the study of older but more extreme warm intervals in Earth's history. Can extreme warm events like those of the mid-Cretaceous (Wilson and Norris, 2001) and the Paleocene-Eocene Thermal Maximum

(PETM; Zachos et al., 2005; Weijers et al., 2007) be used to make predictive models that are of value today? Were other forcing mechanisms that are not known today operative in those events? These extreme departures from 'background' climate should be manifested in high-resolution records of the hydrologic cycle (Kraus and Riggins, 2007), atmos-pheric and oceanic circulation, and vegetation dynamics on land. A concerted and coordinated effort to examine time-equivalent studies over the widest possible geographical range is one approach to globally quantifying the precursor conditions and effects of these extreme warm events themselves.

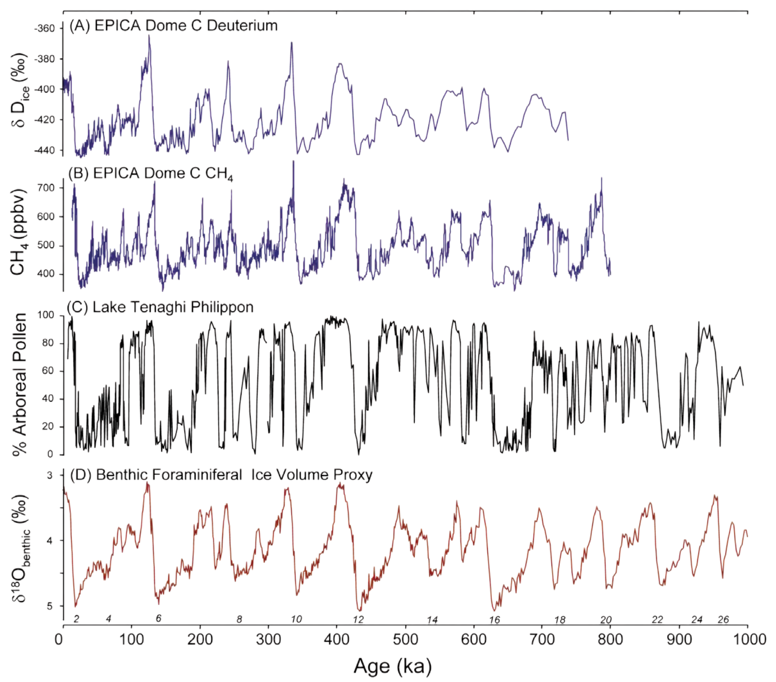

Figure 4. A one million year comparison of ice core and marine core data to a terrestrial record of pollen variability from Lake Tenaghi Philippon, Greece. (A) δD temperature proxy from Epica Dome C ice core, Antarctica (EPICA Community Members, 2004); (B); EPICA Dome C record of atmospheric methane concentrations (Loulergue et al., 2008); (C) percentages of arboreal pollen in sediments from Lake Tenaghi Philippon, Greece (Tzedakis et al., 2006); (D) composite benthic foraminiferal $\delta^{18}O$ proxy for global ice volume variations, with glacial marine isotope stages labelled as 2 to 26 (Liesecki and Raymo, 2005). Note that the pollen record shows clear evidence of orbital and sub-orbital scale vegetation responses to Quaternary climate change and illustrates the potential for recovering long, continuous sediment sequences in lacustrine settings.

Ocean-Continent Interactions

IODP and ICDP can make significant potential contributions to understanding past climate variability connected to the Ocean-Continent Interactions theme. This theme is as broad as it is central to human societies. For example, regional sea-surface temperature variability fundamentally affects heat and moisture supplies to nearby continents ("upstream" effects) (Shanahan et al., 2009), such as in the major low-latitude monsoon systems. Understanding monsoon dynamics under different climate regimes (Wang et al., 2005) is of critical importance because a significant fraction of the human population depends on the monsoons and their life-giving rains for survival. Furthermore, investigating the interrelationships between climate, biotic evolution, and human cultural development will continue to define the effects of abrupt climate change (including droughts and floods) on life (Bartov et al., 2003; Haug et al., 2003; deMenocal, 2004). On the continents, "downstream" effects such as changes in continental weathering, hydrologic balance, and vegetation response can be reconstructed based on terrestrial archives such as lakes (Baker et al., 2001; Cheddadi et al., 2005). Oceanic archives recovered adjacent to the continents also record the direct influence of continental inputs, such as sediment from rivers and winds, and nutrients that play an important role in near-coastal bioproductivity and biogeochemical cycling (Mulitza et al., 2008).

Ocean-continent interactions in the high latitudes have been shown to have far-reaching effects on climate variability on all timescales. Investigating the extent of continental ice sheets, timing of ice sheet ablation, and relationships between Northern Hemisphere and Southern Hemisphere high-latitude climate (European Project for Ice Coring in Antarctica (EPICA) Community Members, 2006) are fundamental to understanding the role of the oceans and ice sheets in abrupt climate change. These studies depend on improved proxies of ice sheet dynamics, sea-ice, meltwater input, and sediment provenance, among others. Furthermore, scientific drilling has just begun to elucidate the connections between high-latitude climate and low-latitude hydrology—for instance, the teleconnections between sea ice and monsoons or sea ice and the position of the ITCZ (Broecker, 2006).

One challenge the community will face in these efforts is the difficulty of finding paired ocean and continent archives in appropriate locations and with adequate resolution to investigate upstream and downstream processes. Nevertheless, new opportunities for enhancing the study of ocean-continent linkages are emerging from the recent integration of novel proxies for continental hydrology and vegetation (e.g., elemental ratio data in bulk sediments, molecular and isotopic composition of leaf waxes; Schefuss et al., 2005; Huang et al., 2007) with classic proxies such as dust, pollen, and clay mineralogy, which can be found in both oceanic and continental archives. Accordingly, workshop participants specifically recommended that scientific drilling proposals on ocean-continent interactions be solicited that focus on three broad topics of critical interest: (1) the major low-latitude monsoons, (2) the hydrologic balance in continental regions critical for human societies, and (3) ice sheet dynamics (Clarke, 2005), all of which will enhance understanding of abrupt climate change.

Biogeochemical Cycles

The cycling of biogenic and geochemical fluxes has important effects on all Earth systems. However, the large number of unknowns associated with these cycles must be addressed at the highest possible resolution if past climate changes and all their complexities are to be correctly evaluated and future changes realistically predicted. We should know what role changes in the carbon cycle played as forcing or feedback during past climate changes (Cao and Woodward, 1998). In the endeavor to find analogues and to produce predictive models for ongoing climate warming, questions have to be addressed about the biotic response to ocean acidification (Fabry et al., 2008), the range of glacial-interglacial CO_2 variability, and the controls on atmospheric greenhouse gas composition as recorded in ice cores.

The employment of high-resolution sedimentary records in these contexts has great strengths and advantages; not only does high-resolution sampling more accurately reveal the details and complexities of the system (e.g., better definition of the climate norm and anomalies), but it is also more likely to yield un-aliased climate signals. In order to understand the specific workings of the climate system under different boundary conditions, we must undertake investigations of the carbon cycle using well-dated, well-calibrated, high-resolution records. Fundamental questions that remain to be answered include the following: What is the role of the carbon cycle in the transition from 41-kyr to 100-kyr cycles in the mid-Pleistocene (Fig. 4; Bintanja and van de Wal, 2008)? What is the role of ocean circulation in the carbon cycle, and how does carbon storage affect the cycle? What is the impact of carbon storage on metal cycles, and how useful are non-traditional metal isotope systems for tracing global paleoenvironmental change? What affects the CO_2 exchange between the surface ocean and the atmosphere on different timescales (Bender et al., 1994)? Is there a threshold level of CO_2 when the oceans switch to a different mode? In addition, the higher frequency behavior of the carbon cycle during the extreme warm climates of the mid-Cretaceous and PETM should be investigated at the highest possible resolution in order to gain insights into the possible extremes of our future world.

Ecosystem Change and Biodiversity

The resilience of ecosystems to climate change is of critical importance in the face of projected warming and altered precipitation regimes (Cramer et al., 2001; Parmesan, 2006). Determining whether systems bend or break under climate loading and where tipping points occur from one state to another can be profitably investigated through high-resolution paleoclimatic records. Indeed, a critical insight into paleoclimates is that they behave non-linearly, with sudden changes of direction. Determining the ecosystem impact of such events will require improved understanding of taphonomy, higher taxonomic resolution (possibly DNA-based identifications), and finer temporal resolution sampling than has commonly been applied, especially in terrestrial sequences. Long, high-resolution terrestrial records of past climate variability comparable to those of marine and ice cores must be studied (Fig. 4; Tzedakis et al., 2006). The 1-Myr-long record from tropical Lake Bosumtwi (Koeberl et al., 2007) and the 3-Myr record from the arctic Lake El'gygytgyn (Brigham-Grette et al., 2007) are outstanding examples that such archives can be found.

The impact on ecosystems of the arrival of new agents of change—such as humans or fire, or the cascading consequences of extinctions and immigrations—are additional issues that need to be resolved. Because terrestrial ecosystems are where people live, work, and generate the majority of global income, it is essential that their responses to climate change are understood and, if possible, anticipated.

Towards The Development of Synergies and Strategies

Other important discussions at the workshop focused on the practicalities of adopting a synergistic approach to climate research and of how to improve present techniques and develop new ones. There were strong feelings in common among the participants that a more tightly coordinated collaboration between paleoceanographers, terrestrial paleoclimatologists, paleoglaciologists, and modelers is required for climate change science to move beyond incremental advances.

There was lively debate about the nature and quality of the various proxies used to infer past climatic and oceanographic conditions. People acknowledged that there needs to be a more universal understanding of the limitations of proxies specific to each segment of the paleoclimate community in order to improve the correlation and synthesis of existing and future records. In particular, proxy development should focus on providing more quantitative data for climate modeling. Existing proxies need to be re-examined; we have the capacity to measure/analyze an ever-widening suite of sediment parameters, but do we always know what they mean/represent?

It is clear that there is a different culture of sampling between the ice core and marine/terrestrial communities. The latter tend to divide a core in time, while ice core groups tend to take each sample and divide it among multiple investigators. In order to maximize the information gained, highly coordinated research efforts are needed that focus on multiple proxies. In the future, cooperating groups will need to acquire more sediment than is presently considered necessary to allow for the many proxies now possible to analyze. This could be achieved by drilling wider diameter cores and/or additional parallel holes. Close coordination between separate investigating groups (e.g., shipboard versus non-shipboard) needs to be established early in the process of planning for drilling projects. In addition, the widest possible range of questions that could be addressed by analyzing the sediment should be considered right from the start, and thus the planning requirements of each potential investigating group could be met. This type of forward planning will be necessary to achieve coordinated temporal and spatial arrays.

To the extent that existing material from previously drilled sites is available, these archives should be used when practical to address new problems and/or apply new techniques whose development postdates the drilling and first wave of science to emerge. With regards to the acquisition of new sediment, core quality is critical. Scientific drilling has gone on long enough that many individuals with longstanding experience have moved on or retired. To avoid costly mistakes and wasted time, records of how best to core particular types of sediments should be kept so that this experience is not lost.

The continuing improvement of standard chronological techniques and the development of new methods are necessary prerequisites to producing high quality high-resolution climate records. Ideally, chronologies should be absolute, as can be achieved by the counting of annual layers in ice cores or distinct varves in lacustrine or marine sediments. In the absence of absolute age control, dating is usually based on a combination of techniques including radiocarbon, foraminiferal oxygen isotope stratigraphies (in marine sequences), paleomagnetism, and tephrochronology. In addition, new techniques that are under development include exposure dates on tufa (Rich et al., 2003); optically stimulated luminescence (OSL) dating at millennial resolution (Stevens et al., 2007); U/Th for tephra chronologies (Farley et al., 2002); development of microtephra stratigraphy (Freibel, 2008); measurements of iridium flux (Gabrielli et al., 2004); and stable isotope correlations with speleothems (Lorrey et al., 2008). A new method of ice core dating being explored involves N_2/O_2 variations in the ice at Dome Fuji tuned to local insolation at 70°S (a method that assumes no lag between insolation forcing and the N_2/O_2 response; Kawamura et al., 2007). Such an N_2/O_2 timescale is potentially very useful to the combined marine and ice core communities and will likely be adopted if it can be shown that paleointensity can be correlated to cosmonuclides. To be able to apply this to high-resolution sediment studies means that the magnetic paleointensity record has to be systematically developed from marine sections with millennial-scale records. Paleointensity records tend to be better in high latitude/low oxygen environments, and sediment drifts are an ideal archive (Channell et al., 2000). Locations need to be systematically sought out in order to build up paleointensity databases needed for calibration of the Quaternary.

There was considerable discussion over the concept of developing marine 'reference' cores akin to the long ice core records for better global correlation of climate records. The Greenland ice core records have become, almost by default, the de facto "type-section" for late Pleistocene climate change in that they serve as the measuring stick against which other climate records are inevitably compared. One drawback, however, is that the ice cores represent conditions at essentially one location in the high northern latitudes and are inappropriate for study of much of the climate system (Shackleton et al., 2000, 2004). The development of a counterpart series of marine reference sections would require the generation of a few internationally coordinated, multi-replicated, multi-parameter, high-resolution records (Fig. 5; Alley, 2003). However, it was acknowledged that the great size and horizontal and vertical variability in the oceans make identification of a "few" reference sections a difficult task. In selecting the locations for such reference sites, it was felt that drilling targets should be chosen so as to address specific paleoclimatic questions rather than locating them simply to achieve some degree of geographic coverage. For example, a reference section for understanding the MOC might actually consist of a depth

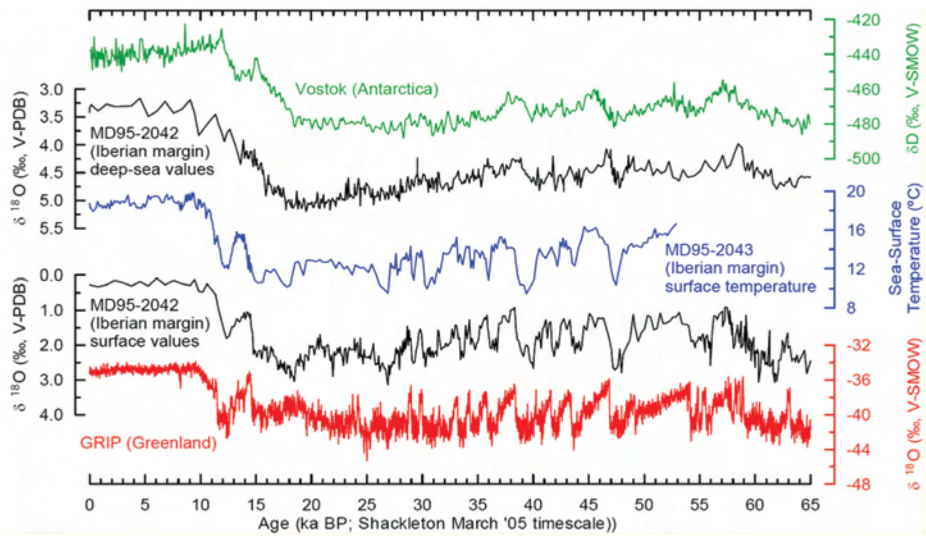

Figure 5. The development of a limited number of well-dated marine 'reference sections' for the late Quaternary would serve as a valuable complement to Greenland and Antarctic ice core records, which by their nature only record high-latitude processes in the two hemispheres. One recommended location for such a reference section is off the southwest coast of Iberia (see no. 35 with 'star' in Fig. 6) near the site of long Calypso cores MD95-2042 and MD95-2043, for which pre-existing data (Shackleton et al., 2000, 2004) have already demonstrated high and uninterrupted sedimentation rates and a clear record of abrupt climate events in the mid-latitudes that can be correlated to those in Greenland. Extending the record at this site to encompass multiple glacial-interglacial cycles can only be accomplished by scientific ocean drilling.

transect, while reference sections for ENSO could consist of drilled sequences from El Niño-sensitive areas such as Indonesia or Tahiti. If such a suite of marine reference sections can be developed over time, they will provide marine sediment analogues to the polar ice cores, but will be temporally and spatially more extensive.

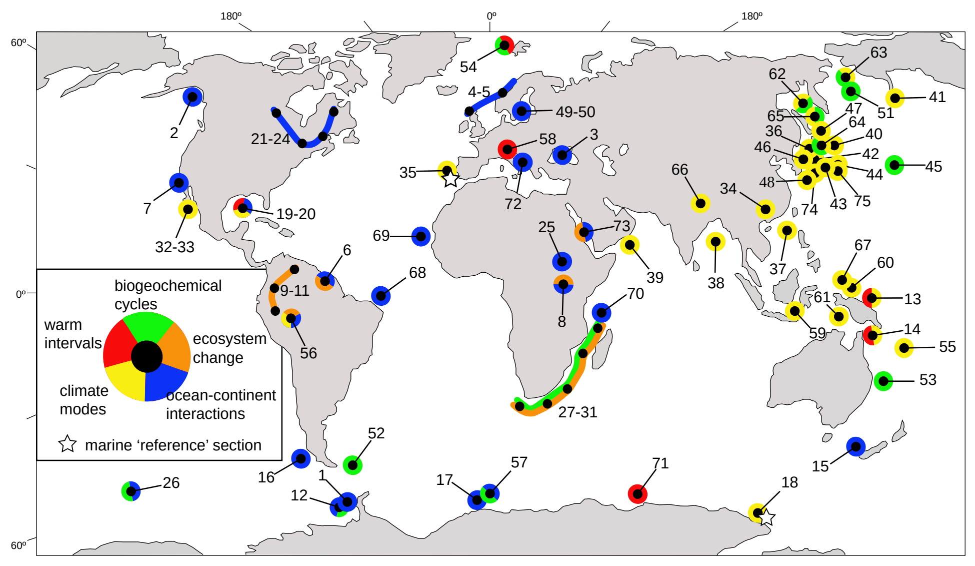

Figure 6. Compilation of potential drilling sites proposed by workshop participants to address the five "petal" themes of the flower diagram shown in Fig. 3. Site numbers are linked to information that can be found in Appendix 1 (http://high-resolutoin.icdp-online.org).

As part of the workshop, participants were asked to submit information on potential targets for high-resolution continental and oceanic drilling that satisfied specific requirements of record length and resolution (annual to millennial) and which address questions related to the key research themes highlighted in Fig. 3 and this report. The resulting array of drilling targets, identified in Fig. 6 and keyed there to theme and to the site-specific information listed in Appendix 1, shows that an impressive number of locations are available globally where the potential exists to recover sedimentary sequences suitable for high-resolution study. The themes/targets incorporate many sites already in the review system as part of existing ICDP/IODP drilling proposals (Appendix 1, http://high-resolution.icdp-online.org).

A series of four hypothetical transects emerged from discussions as potential examples of how combined IODP and ICDP drilling could maximize scientific progress in paleoclimate research. These are presented here to illustrate how strategically placed sites can be combined to address broad climate questions and themes.

1) The Core ENSO Signal and Teleconnections. Much can be learned about ENSO and its behavior through time, based on a combined land/sea transect from SE Asia/Papua New Guinea via Pacific Islands to the west coast of South and Central America. This might incorporate both high deposition rate marine records and drilled coral sequences spanning the tropical Pacific, as well as lakes along the western edge of the Americas. In addition, records from regions such as northeast Brazil, South Africa, and New Zealand that are strongly teleconnected to ENSO today would provide important information as to whether these linkages persist through time under different global boundary conditions.

2.) Baikal to Bengal. A roughly north-south transect was envisioned that would focus on the internal dynamics of the Asian monsoonal system. This would include sites spanning the latitude range from the Siberian arctic Lake El'gygytgyn to Lake Baikal to the Bengal Fan system, with potential intermediate sites located in the Amur River, the Tibetan Plateau and vicinity, India, and the Ganges Plain. Adding sites in and around the Arabian Sea would broaden the set of addressable questions by tying in regions affected instead by the Indian monsoon.

3.) Southern Hemisphere Tropics (South America) to Southern High Latitude Interactions. Southern hemisphere climate records are currently limited in number, but potential exists to drill latitudinal transects of sites ranging from the southern tropics of South America into the high southern latitudes, both on land and in coastal waters where high sedimentation rate sequences are most likely to be found. It was generally felt that South America offered an important opportunity in the southern hemisphere to develop a comprehensive regional database of sites.

4.) The Bipolar Seesaw, North-South Gradients, and Interhemispheric Linkages. Records from the last glacial indicate that the abrupt warmings and coolings recorded in Greenland ice appear to be out of phase with their counterpart temperature excursions in the high-latitude Southern Hemisphere, an observation consistent with changes in the Atlantic's meridional overturning circulation and its effects on ocean heat transport (EPICA Community Members, 2006). We know little about whether this "bipolar seesaw" is operative at other times in the past and of how changing temperature gradients affect such climatic variables as the distribution of tropical precipitation and ITCZ position. Transects of drill sites on land and in the ocean spanning the high to low latitudes in both hemispheres are the only way to examine how gradients and interhemispheric linkages have varied through time.

As already noted, workshop participants endorsed the concept of developing a limited number of globally distributed marine reference sections for the purpose of calibrating Quaternary climate at high resolution in key regions. It was recommended that one such early target area should be offshore of the southwest coast of Iberia (Figs. 5, 6) where high sedimentation rates, record continuity, and tight linkages to the rapid climate excursions in Greenland have already been demonstrated. In addition, a large data set of proxy records already exists from this location (Cayre et al., 1999; Sanchez-Goñi et al., 1999; Shackleton et al., 2004; Skinner et al., 2003), so we know that sediments are amenable to analysis using a wide variety of methods.

Proxy data generated from high-resolution geologic archives will seldom lead to an improved understanding of how the climate system works if those data are not linked into modern thinking about climate dynamics and integrated into an Earth-system modeling approach. The presence of modelers at the workshop ensured that data-model integration was a prominent component of the discussions.

Integration of Paleoclimatic Data and Earth-System Modelling

Over the past years Earth-system modeling has become increasingly important in the area of paleoclimatic research. Specifically, physically based models provide a valuable tool to assess conceptual models of past climate changes derived from paleoclimatic data. In addition, data-based reconstructions of past climate variations provide critical test grounds for Earth-system models that are usually tuned to capture present-day climate. Accordingly, combining data-based reconstructions and paleoclimate modeling offers a promising track to fully comprehend past climate dynamics and to test models used for assessing future climate changes (Ramstein et al., 2007; Mulitza et al., 2008).

Specific benefits that can result from the joint utilization of paleoclimatic reconstructions and paleoclimate modeling include a means for formulating and testing hypotheses (e.g., by quantifying the response of the climate system to known or potential forcings). Moreover, climate models provide a comprehensive framework for exploring couplings and feedbacks between the various components of the climate system. This type of analysis is of special relevance for detecting thresholds in the climate system. Finally, Earth-system models offer a link between past climate changes and projections of future climate, which is assessed by the same type of models.

The combination of paleoclimatic reconstructions and Earth-system modeling is thus very forward-looking with respect to disentangling climate dynamics on timescales of societal relevance. Both IODP and ICDP have the obligation to underpin the efforts of the IPCC in reducing the uncertainties associated with the projections of future climate changes. A pivotal contribution of paleoclimatic reconstructions arises through the possibility of testing IPCC-type Earth-system models beyond the range of climate variability documented by the instrumental record. A research strategy following this path would involve modelers from the early planning stage of an IODP or ICDP project. Such collaboration would not only allow for setting up joint hypotheses to be tested but also to choose drilling locations most sensitive to specific climate changes.

Summary and Recommendations

The Potsdam workshop attracted an overwhelming response from the paleoclimate community, and the enthusiastic discussions and debates that took place clearly demonstrated that the topic of scientific drilling of high-resolution archives is hot, timely, and widely interesting to the scientific community. Great synergy already exists between IODP and ICDP in the field of paleoclimate research. Workshop participants clearly felt that having these two programs work together to jointly address the key research themes identified in Potsdam (the "petals" of Fig. 3) is the most promising way forward.

We recommend that further strengthening of the links between IODP and ICDP be a goal of the leadership of both programs. Each program brings state-of-the-art drilling technology to bear on scientific questions that only these programs—and the research communities they support—can answer. Cooperation should also be sought with other major programs devoted to paleoclimate sampling, including IPICS (International Partnership for Ice Core Sciences) and IMAGES (International Marine Global Change Study). Climate, by its very nature, is a complex system, and neither land-based nor marine-based records are sufficient by themselves to provide a complete picture of the system's workings through time.

Closer cooperation between IODP and ICDP ideally should be extended to have standard procedures for core processing and treatment, agreed-upon suites of standard measurements and protocols, policies for data integration, and perhaps even common curation of cores. One obvious indication of a closer working relationship between the programs—and that would seem simple to achieve—would be to have site locations for ICDP drilling and links to the data included on the searchable online IODP digital site map. This would facilitate planning efforts for some of the large-scale transect opportunities envisioned at this workshop.

Continued development of drilling capabilities should be a high priority. Within ICDP, there seems to be a gap in drilling technology for the recovery of sediments between about 20 m and 100 m penetration (i.e., what can be achieved with standard piston coring and by deep drilling using the GLAD rig). We should also further explore the possibility of increasing core diameters in both programs to allow for larger sediment volumes for multi-proxy studies. Finally, increased flexibility in the duration of drilling campaigns, especially within IODP, would greatly facilitate the planning and proposal process for many high-resolution sites where sediments can often be recovered relatively quickly and efficiently.

The Potsdam workshop left no doubt that scientific drilling is absolutely critical to the future of paleoclimate research. The large array of potential drilling targets summarized here, together with the concept of transects and climate reference sections put forth, should ensure that high-resolution records appropriate for investigating the climate research themes identified in this report are available to the community at large.

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Testing the Extensional Detachment Paradigm: A Borehole Observatory in the Sevier Desert Basin

by Nicholas Christie-Blick, Mark H. Anders, Gianreto Manatschal, and Brian P. Wernicke

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Low-angle normal faults or detachments are widely regarded as playing an important role in crustal extension and the development of rifted continental margins (Manatschal et al., 2007). However, no consensus exists on how to resolve the mechanical paradox implied by the gentle dips of these faults and by the general absence of evidence for associated seismicity (Sibson, 1985; Wernicke, 1995; Axen, 2004). As part of a new initiative to rationalize geological and geophysical evidence and our theoretical understanding of how rocks deform, a group of forty-seven scientists and drilling experts from five countries met for four days on 15–18 July 2008 to discuss the present status of the paradox and a borehole-based strategy for resolving it. The workshop was held at two venues in Utah (the Utah Department of Natural Resources in Salt Lake City, and Solitude Mountain Resort in the adjacent Wasatch Range), with a one-day field trip to the Sevier Desert basin of west-central Utah (Figs. 1, 2) to examine the general setting of potential drill sites and the footwall geology of the Sevier Desert detachment (Canyon Range).

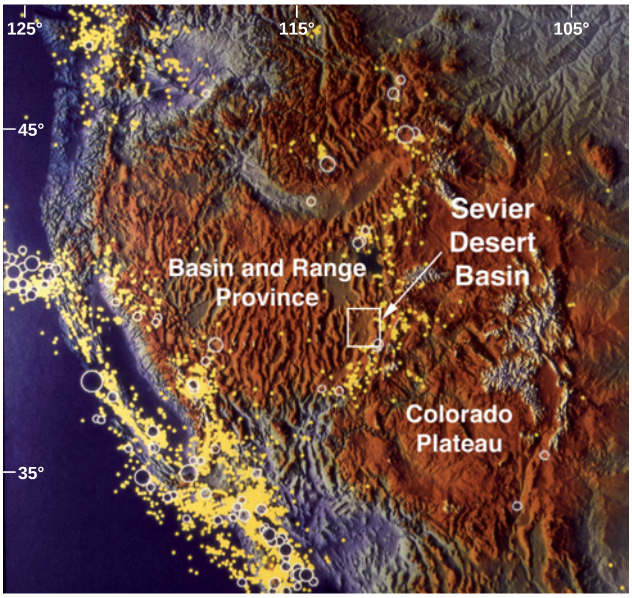

Figure 1. Regional physiography, seismicity, and location of the Sevier Desert basin in the western United States (from Simpson and Anders, 1992). White open circles are earthquakes greater than magnitude 6.0 from 1900 to 1975. Yellow dots are earthquakes greater than magnitude 2.5, occurring between 1970 and 1985. The north-trending band of seismicity adjacent to the Sevier Desert marks the eastern edge of the Basin and Range Province. Intense seismicity to the west and southwest, and including the western Basin and Range Province, corresponds with the diffuse transform plate boundary of which the San Andreas fault system is the most important element.

Interest in the Sevier Desert detachment (Fig. 3) relates to its large scale, geometric simplicity, severe misorientation with respect to σ_1, comparatively shallow depth, and compelling evidence for contemporary slip, as well as its accessibility from more or less flat public land (Von Tish et al., 1985; Niemi et al., 2004; Wills et al., 2005). The fault was first recognized in the mid-1970s, on the basis of seismic reflection data and commercial wells, as the subsurface contact between Paleozoic carbonate rocks and Cenozoic basin fill (McDonald, 1976). It is thought by most workers to root into the crust to the west of the Sevier Desert, to have large offset (as much as 47 km; DeCelles and Coogan, 2006), and to have been active since the late Oligocene at or near its present dip of 11° (GPS data and prominent Holocene scarps on steeply inclined hanging-wall faults that appear to sole downward into the detachment; Von Tish et al., 1985; Oviatt, 1989; Wernicke, 1995; Niemi et al., 2004). Whether the detachment fault crops out today at the eastern margin of the Sevier Desert basin is unresolved (Otton, 1995; Wills and Anders, 1999). No modern scarps have been observed there. Although no historic seismicity has been documented on the detachment, its scale is consistent with earthquake magnitudes at least as large as Mw = 7.0 (Wernicke, 1995). It is also possible that slip is currently taking place by aseismic creep. While dozens of low-angle normal faults have been recognized, at numerous locations in both extensional and orogenic settings—and by low angle we refer to the dip of a fault today, not necessarily its dip when it was active—the Sevier Desert detachment is one of very few that is sufficiently well-documented, active, and accessible from the surface that it might reasonably yield new insights about the conditions under which such faults slip.

A two-step drilling strategy emerged during workshop discussions. The first step (a pilot hole) is to re-enter one of several wells drilled by petroleum companies in the Sevier Desert basin (Wills et al., 2005), to deviate a few tens of meters above the base of the Cenozoic section, and to core through the detachment level to at least several tens of meters below the top of the Paleozoic section. Before embarking on a dedicated main hole, it is imperative to demonstrate that a fault is present (i.e., that fault rocks are present). The detachment interpretation, though generally accepted, currently depends entirely on geophysical data, not direct observation. It may be necessary to deviate and core through the detachment more than once to obtain definitive samples. The well provisionally selected for the pilot hole, and for technical as well as geological reasons, is ARCO Hole-in-Rock in the southern Sevier Desert (AHR in Figs. 2, 3B). The detachment is sufficiently deep at the Hole-in-Rock well (2774 m), and its hanging-wall offset is sufficiently large that fault rocks ought to be well-developed in both Cenozoic strata above and Paleozoic strata below. At the same time, the existence of late Pleistocene to Holocene fault scarps to the east of the well is consistent with recent displacement on the detachment at this location.

The second step (main hole) is to core, log, and make *in situ* measurements at a location between a few tens of meters and 4 km west (downdip) of ARCO Hole-in-Rock, and intersecting the interpreted detachment at a depth of 2800–3500 m (Fig. 3B). All surface scarps appear to be east of the Hole-in-Rock well at this latitude. The selection of a site 4 km or more to the west of ARCO Hole-in-Rock would permit the detachment fault to be penetrated within Paleozoic or Neoproterozoic strata west of the intersection between the basin's western bounding fault and the detachment.

The principal objective of the second hole is to establish an observatory at a depth and location most likely to allow monitoring of the full rate of extension across the Sevier Desert (~0.35 mm yr^{-1}; Niemi et al., 2004), and yet not so deep as to be prohibitively expensive. Among *in situ* measurements to be made in the vicinity of the detachment are the following: pore pressure, fracture permeability, fluid chemistry (including He), temperature, the orientation of stress axes, and the magnitude of differential stress. A borehole seismometer will be installed as part of a local array. A second objective of this main hole is to investigate the history of sediment accumulation and how the timing of basin development relates to exhumation of the detachment's footwall (based upon already published fission-track data for the Canyon Range; Stockli et al., 2001). A full suite of downhole logs (especially acoustic logging) will allow confident correlation with seismic reflection data. A byproduct of stratigraphic and geochronological analyses will be an extended lacustrine record of continental climate change since the late Oligocene.

A priority before any drilling is undertaken is to acquire new seismic reflection data in a grid encompassing both ARCO Hole-in-Rock and candidate locations for the proposed main hole. These data will be essential in establishing confidence in three-dimensional stratigraphic and structural geometry. Other pre-drill data that may be particularly useful—among many excellent ideas raised at the workshop—are high-resolution seismic and GPR (ground-penetrating radar) data combined with trenching across prominent fault scarps, and the establishment of closely spaced GPS stations aimed at determining more precisely how contemporary extension is distributed across the Sevier Desert.

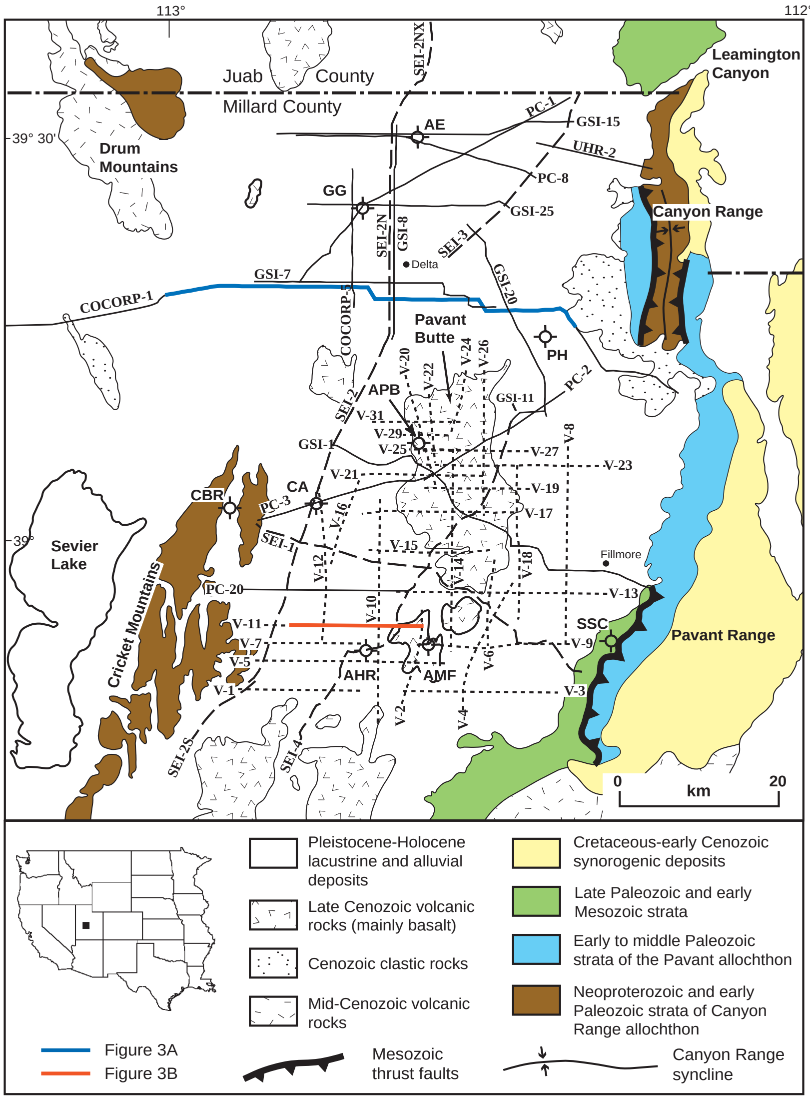

Figure 2. Generalized map of the Sevier Desert basin, west-central Utah, showing locations of wells and seismic reflection profiles (from Wills et al., 2005; see Fig. 1 for location). Wells: AE, Argonaut Energy Federal; AHR, ARCO Hole-in-Rock; AMF, ARCO Meadow Federal; APB, ARCO Pavant Butte; CA, Cominco American Federal; CBR, Chevron Black Rock; GG, Gulf Gronning; PH, Placid Henley; SSC, Shell Sunset Canyon. Solid, dashed, and dotted lines correspond with different seismic datasets. Part of Consortium for Continental Reflection Profiling (COCORP) Utah Line 1 (blue) is shown in Fig. 3A. A portion of Vastar Resources, Inc. Line V-11 (red) is shown in Fig. 3B. Thrust faults are the tightly folded Canyon Range thrust in the Canyon Range and the structurally lower Pavant thrust in the Pavant Range (teeth on upper plate). Inset map shows location relative to states in the western U.S.

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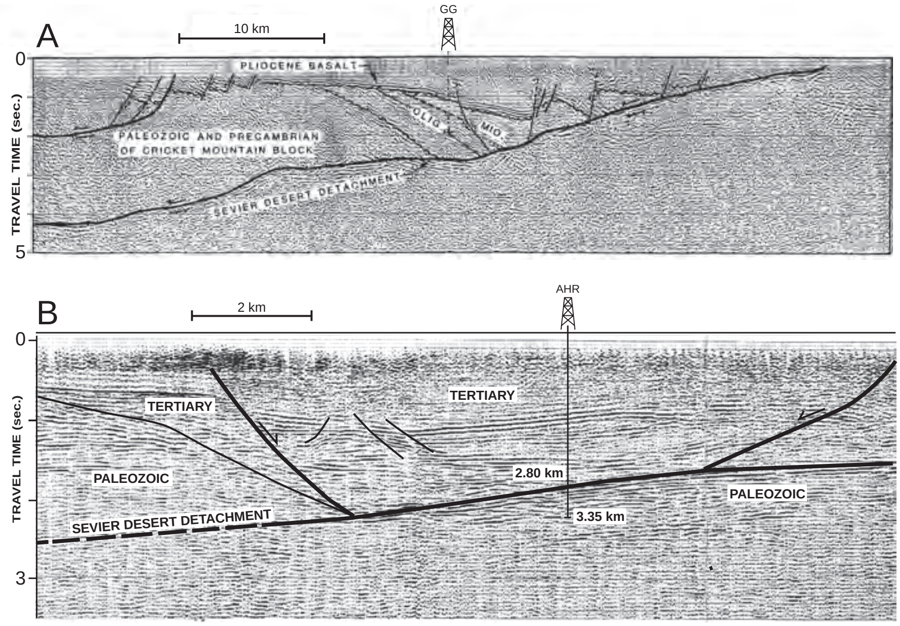

Figure 3. Examples of seismic reflection profiles from the Sevier Desert basin (see Fig. 2 for location). [A] Part of COCORP Utah Line 1, with interpretation of the Sevier Desert detachment from Von Tish et al. (1985). [B] A portion of Vastar Resources, Inc. Line V-11, with interpretation modified from Planke (1987). Projected wells: GG, Gulf Gronning; AHR, ARCO Hole-in-Rock. Line V-11, located ~3 km north of the Hole-in-Rock well, is the profile that best illustrates the geological structure in the vicinity of the well.

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Understanding Paleoclimate and Human Evolution Through the Hominin Sites and Paleolakes Drilling Project

by Andrew Cohen, Ramon Arrowsmith, Anna K. Behrensmeyer, Christopher Campisano, Craig Feibel, Shimeles Fisseha, Roy Johnson, Zelalem Kubsa Bedaso, Charles Lockwood†, Emma Mbua, Daniel Olago, Richard Potts, Kaye Reed, Robin Renaut, Jean-Jacques Tiercelin, and Mohammed Umer

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Understanding the evolution of humans and our close relatives is one of the enduring scientific issues of modern times. Since the time of Charles Darwin, scientists have speculated on how and when we evolved and what conditions drove this evolutionary story. The detective work required to address these questions is necessarily interdisciplinary, involving research in anthropology, archaeology, human genetics and genomics, and the earth sciences. In addition to the difficult tasks of finding, describing, and interpreting hominin fossils (the taxonomic tribe which includes *Homo sapiens* and our close fossil relatives from the last 6 Ma), much of modern geological research associated with paleo-anthropology involves understanding the geochronologic and paleoenvironmental context of those fossils. When were they entombed in the sediments? What were the local and regional climatic conditions that early hominins experienced? How did local (watershed scale) and regional climate processes combine with regional tectonic boundary conditions to influence hominin food resources, foraging patterns, and demography? How and when did these conditions vary from humid to dry, or cool to warm? Can the history of those conditions (Vrba, 1988; Potts, 1996) be related to the evolution, diversification, stasis, or extinction of hominin species?

Most of the efforts to address these questions to date have centered on evidence from outcrops where the hominin fossils have been collected. Earth scientists have made great strides in understanding these contextual questions using fluvial, paleosol, and marginal lacustrine sediments associated with hominin fossils; however, this approach has its limitations. Outcrops, for example, cannot normally provide us with continuous, unweathered stratigraphic sections needed to address many questions relating events in hominin evolution and environmental change. The places where hominins actually lived (literally, above the water table) tend to have only discontinuous and relatively low resolution lithostratigraphic records of climate and other aspects of environmental change.

For these reasons the paleoanthropology community has turned to drill cores as a potential source of more highly resolved paleoenvironmental information. This concept is not new. Almost thirty years ago, the U.S. National Science Foundation (NSF) sponsored a workshop to examine the potential of recovering long sediment cores from the deepest and oldest of the modern African Rift Valley lakes, with a particular emphasis placed on how these records might inform our understanding of the environmental context of early hominin evolution (Lewin, 1981). In an influential paper, deMenocal (1995) demonstrated how northeastern African paleoclimate could be inferred from dust records encased in Deep Sea Drilling Project (DSDP) drill cores collected in the Gulf of Aden. This paper, as well as subsequent ones (deMenocal,

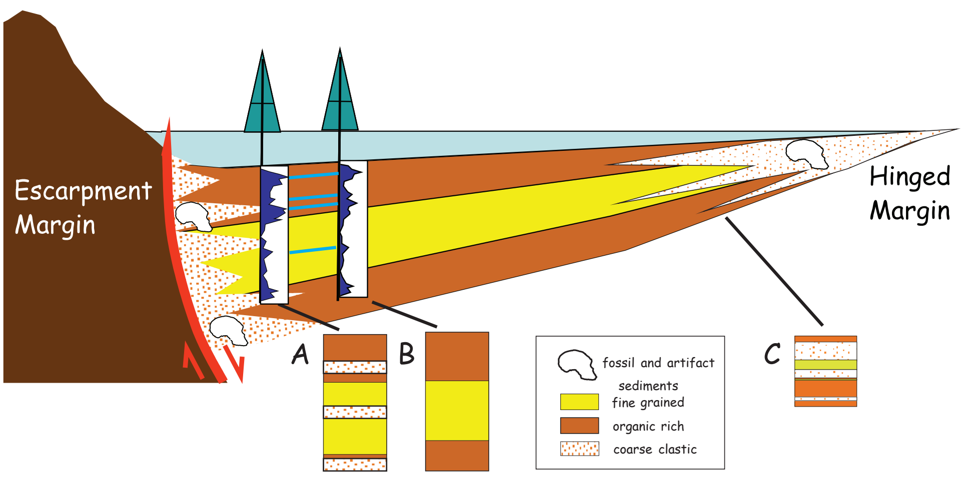

Figure 1. A conceptual model for drill site targeting in HSPDP (Hominin Sites and Paleolakes Drilling Project), using a half-graben rift basin depositional model. Note that a lake is shown in the diagrammatic cross section, although for the current phase of drilling we are targeting paleolake deposits where drilling from a barge can be avoided. The primary target (Drill Site B) would be far enough from the paleoshoreline to avoid most coarse clastic facies (pattern), with a relatively thick and highly resolved stratigraphic record. These types of offshore (fine-grained, organic rich) sediments (shown as yellow and brown solid colors) are most likely to yield the continuous paleoclimatic records useful for addressing current questions about hominin evolution/climate interactions. In contrast, a hinged margin site (C), even though potentially in close proximity to fossil and artifact localities, will yield a thinner and more discontinuous record, and one in which high stand lake deposits are over-represented. A more proximal target on the escarpment margin (A) will yield a dominantly coarse-grained stratigraphic record that is also less desirable for paleoclimate studies, although it may provide a useful secondary target for correlation into the hominin-bearing outcrops and/or records of tectonic uplift affecting the watershed.

2004; Feakins et al., 2005) by the same research group, provided the first more-or-less continuous offshore record of Neogene climate for hominin evolution occurring nearby terrestrially, and also set out a research agenda for investigating the possible role of orbital forcing mechanisms on the timing of hominin evolution. The idea of drilling the African Great Lakes ultimately came to fruition in 2005 with the successful completion of the Lake Malawi Drilling Project (Scholz et al., 2006), which had important paleoclimate implications for hominin evolution and the expansion of anatomically modern humans out of Africa (Cohen et al., 2007).

Despite these successes, the role of scientific drilling in answering questions of importance to paleoanthropology is still hampered by the location of the drill core records currently available relative to where hominin fossils have actually been found. Both the Gulf of Aden and Lake Malawi lie at considerable distances from the important fossil hominin and artifact sites in East Africa. Additionally, in the case of the DSDP dust records, the signal itself integrates climate history over a vast area of northeastern Africa and Arabia. To address questions about local environmental conditions, a drilling effort was needed to specifically target these regions. The Hominin Sites and Paleolakes Drilling Project (HSPDP) grew out of this need.

During 17–21 November 2008, over sixty scientists from thirteen countries met in Addis Ababa, Ethiopia for a workshop entitled "Scientific Drilling for Human Origins: Exploring the Application of Drill Core Records to Understanding Hominin Evolution" to chart a new path forward in the application of drill core studies to understanding human evolution. This workshop followed up on an earlier (2005) meeting on the broader theme of "Paleoclimates and Human Evolution" (Cohen et al., 2006), as well as two years of exploratory research and site surveys at potential drill sites.

Major themes of the 2008 workshop were laid out in introductory talks by Andy Cohen and Rick Potts; they concerned general criteria guiding the HSPDP in its attempt to identify promising drilling sites and what we might learn from drilling that would be of interest to paleoanthropology. Ideal candidate sites for drilling would individually provide cores with very high temporal resolution and continuous records of basin scale environmental history and regional scale paleoclimate, would have the potential for excellent geochronologic control, and would be amenable to a wide range of analytical techniques (Fig. 1). To allow us to address questions of environment/hominin interactions on a local scale, ideal drilling locations would also be in close proximity and be geologically and chronologically related to important hominin fossil and artifact sites. In particular, lacustrine deposits can provide an extraordinary range of paleoecological, geochemical, and sedimentological records of past climate, and typically yield much higher resolution records than coeval fluvial deposits or paleosols. In the East African Rift Valley, we have focused on relatively deep, paleolake deposits within the same depositional basins as important hominin fossil finds. Within rift half-graben lake basins, our search for ideal drilling targets has centered on what would have been the offshore portions of escarpment margins of half-grabens, where water depths would have been deepest and sediment accumulation rates highest over extended periods. Secondary objectives might include collecting cores from more proximal locations to the paleoshorelines, to tie in the paleoclimate records directly to fossil/archaeological sites via correlation and to collect records of tectonic activity and other processes within the watersheds. HSPDP has focused efforts on identifying several basins, spanning a range of "critical intervals" in hominin evolution. By comparing multiple lacustrine records, we have a realistic opportunity to address questions, for example, about the relationship between accurate local climatic records, possible orbital forcing mechanisms, or shorter (millennial scale) events with hominin evolutionary patterns such as adaptive radiations, species appearances, and species extinctions. With a highly detailed environmental record from each targeted basin, we can also compare the evolutionary responses to climate change in other biota to contrast possibly unique hominin responses to environmental variation (Potts, 1996). Interbasinal comparisons will also be critical for evaluating evolutionary hypotheses that invoke interactions between climate forcing and tectonic history in the rift (Sepulchre et al., 2006).

Precise measurements of climate change and rift dynamics may be associated with such things as the origin of *Homo*, major transitions in stone technology, rapid brain size increase, or the dispersal of *H. sapiens*; consequently, the goal is to substantially improve our ability to characterize the environmental factors that can be considered central to an understanding of human evolution.

Interregional and inter-temporal investigations will generate paleoenvironmental data for a series of repeated historical experiments, whose outcomes can be compared. As Potts suggested at the workshop, with drill core records in the basins where hominins have been recovered, we could evaluate the hypothesis that episodes of increased magnitude in environmental variability (e.g., recorded in paleo-precipitation proxies) correlate in time and space with hominin species diversification events and/or technological innovations. Through paleoclimate modeling approaches grounded in better data from core records, we will be better able to understand the dynamics that link climatic and evolutionary histories. Vegetation simulations using fully coupled General Circulation Models (GCMs) have already proven useful for understanding Quaternary climate changes relevant to the evolution of *H. sapiens* (Cowling et al., 2008).

To keep total project costs realistic given a goal of drilling multiple hominin basins, the HSPDP decided early on to pursue on-land drilling targets, accessible by a truck-mounted drill rig, rather than trying to return to extant lakes, where the logistics complexity and costs would be much greater. In 2007, HSPDP received funding from NSF to conduct site logistics and subsurface geophysical surveys at several promising localities (Fig. 2), which were the focus of much of the 2008 workshop discussion. All of these represented areas of long-standing geological and paleoanthropological research, where thick sequences of paleolake deposits occur in close proximity to important hominin or archaeological sites.

Chris Campisano described the scientific opportunities provided by the Northern Awash River Valley in the Afar region (Fig. 3), targeting the Middle Pliocene (~3.8–2.9 Ma) Hadar Formation lake deposits. Nearby fluvio-lacustrine and paleosol deposits of this formation and the overlying Busidima Formation have yielded spectacular fossil and artifact discoveries, including the iconic Lucy, First Family, and Selaam (Dikika baby) fossils, all representing the early hominin species Australopithecus afarensis (Johanson and White, 1979; Johanson et al., 1982; Alemseged et al., 2005; Behrensmeyer, 2008; Campisano and Feibel, 2008; Wynn et al., 2008), as well as the oldest known stone tools (Semaw et al., 1997). All of the *A. afarensis* fossils (representing ~90% of the fossils of this taxon discovered to date) accumulated around the margins of a relatively deep rift lake, the deposits of which would be the target of this drilling project (Fig. 2).

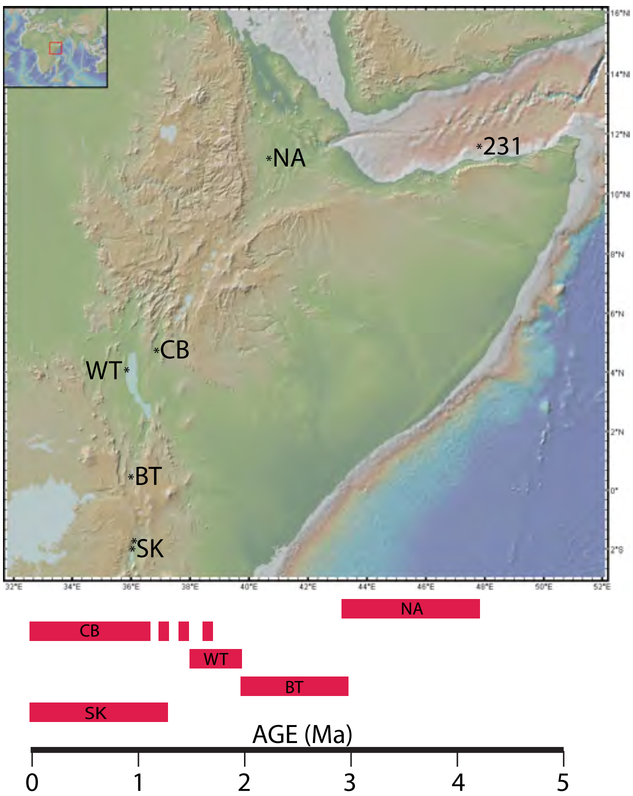

Figure 2. Map showing areas under active consideration for HSPDP drilling and stratigraphic ranges covered by each area. NA=Northern Awash River Valley, Northern Afar; CB=Chew Bahir; WT=West Turkana; BT=Baringo-Tugen Hills; SK=Southern Kenya. Gulf of Aden DSDP Drill Site 231, discussed in the text, is also shown. Base map developed with GeoMapApp©.


Figure 3. Outcrop photo of Middle Pliocene laminated diatomites from near the depocenter of a paleolake in the Northern Afar, one of the likely target locations and intervals for HSPDP drilling. Hill is about 8 m high.

Prior and ongoing geological research have focused drilling exploration efforts on the paleo-depocenter of a large Hadar basin lake, whose depositional cycles appear linked to global climate forcing (Campisano and Feibel, 2007; Dupont-Nivet, et al., 2008). A HSPDP team led by Roy Johnson conducted reflection seismic site surveys of potential drilling targets in this depocenter in 2008 with promising results.

Craig Feibel discussed potential onshore drilling targets on the west side of modern Lake Turkana in northern Kenya (Fig. 2). Plio-Pleistocene deposits rich in artifacts and fossils of hominins and other vertebrates (Harris et al., 1988; Feibel et al., 1989; Roche et al., 2004) accumulated in this region on the margins of large paleolakes (proto-Lake Turkana) (Lepre et al., 2007). A thick sequence of 2.0–1.5-Ma lake beds from one of these lacustrine phases would provide a continuous record of climate and environmental history during a particularly important interval of hominin evolution. Seminal events—such as evolution of several species of our own genus *Homo*, the first long-distance transport of stone tools, and the appearance of Acheulean (e.g., hand axe) types of tools, and the first expansion of hominins out of Africa—all occur during this critical time interval. A HSPDP seismic reflection profile and logistics survey conducted in 2008, coupled with decades of prior stratigraphic research on local outcrops, provide clearly defined drilling targets for sampling the offshore paleolake deposits spanning this interval.

Two areas in the southern Kenya Rift Valley (Fig. 2) that have been evaluated for drilling logistics were also considered in detail. Kay Behrensmeyer explained the potential for drilling around the Pleistocene (~1.2–0.5 Ma) Olorgesailie lake basin. For many years, Olorgesailie has been recognized as one of the most important archaeological sites in the world for documenting Acheulean (and more recently, Middle Stone Age) technology, and the deposits also contain a rich vertebrate fossil record, including hominins (Isaac and Isaac, 1977; Potts and Deino, 1995; Potts et al., 2004).

The fossils and stone tools occur on the margins of a Pleistocene lake, whose diatomaceous sediments would be one drilling target (Behrensmeyer et al., 2002; Owen et al., 2008). A terminal sump for the basin, the Koora Graben, forms another attractive target for obtaining an even higher resolution and more continuous paleoclimatic and paleohydrologic record for the basin. Robin Renaut discussed the potential for drilling nearby Lake Magadi, the second site of interest in the Rift Valley. This soda lake is well-known among sedimentologists and sedimentary geochemists (Eugster, 1980) and is also surrounded by a number of important Early and Middle Pleistocene archaeological and fossil hominin sites. The lake is currently the site of active trona production, making the playa surface readily accessible. It was drilled for mineral exploration purposes in the 1960s (unfortunately, the cores have been lost), and several studies have demonstrated the great potential of this basin for producing high resolution paleoclimate records (Taieb et al., 1991; Damnati and Taieb, 1995). Because Lake Magadi and Olorgesailie are in close proximity (~20 km apart) but occur in completely separate rift sub-basins (see Fig. 2) with no hydrologic connection, drill core records from both could allow paleoanthropologists to separate regional paleoclimatic effects on early hominin habitats from local watershed processes for the first time.

The workshop also provided opportunities to discuss other potential drilling targets. Alan Deino explained the potential for drilling Late Pliocene lake beds from the Tugen Hills region of the Lake Baringo Basin (central Kenya rift). The 3–2-Ma interval encompassed by these lake beds is also a period of important events in this time period, such as the first documented stone tools, the first fossils of *Homo*, and the evolution of several other hominin species. A sequence of well-dated, diatomaceous lake beds in the Tugen Hills area displays strong cyclicity interpreted as correlating to orbital (Milankovitch) time scales, making this an optimal site for testing ideas about linkages between hominin evolutionary events and climatic variability (Deino et al., 2006; Kingston et al., 2007). Giday WoldeGabriel discussed the potential of drilling in the Chew Bahir Basin in southern Ethiopia. This area sits on the interface between the Kenyan and Ethiopian rifts, regions whose biogeographic histories, despite their proximity, appear to be quite distinct. The area is also in close proximity to important Early Pleistocene fossil and archaeological sites (Suwa et al., 2007). The potential drilling target, a playa surface similar to Lake Magadi, will be the subject of preliminary field studies in late 2009. At the conclusion of the workshop, a call to the paleoanthropology and paleoclimate communities was issued by HSPDP for additional suggestions for sites that might be incorporated into future drilling proposals.

Much of the workshop was spent discussing analytical methods that might be used to study the cores collected. The wide range of techniques common to paleolimnological investigations (diatoms, ostracodes, pollen, stable isotopes, scanning XRF, sedimentology) were well-represented by researchers at the meeting. Additionally, leaders in exciting new methods in organic geochemistry, such as the TEX_{86}, MBT, and leaf wax studies, raised the possibility of obtaining much improved quantitative reconstructions of temperature and precipitation for the basins under study. Making the most of all of these methods will require the continuous, unweathered samples afforded only by drilling. Geochronology was a major focus of discussion, with many participants considering how best to transfer our existing (outcrop-based) understanding of the stratigraphy and age models for each basin to core records. Because of the wide range of time scales under consideration, many different techniques will ultimately be used. It was evident from the lively discussion that HSPDP could be a proving ground for new dating and correlation methods and the extension in time of existing ones. Breakout groups considered how coordination between research groups might be achieved between the different drilling areas to obtain intersite comparability. This ultimately will be critical for synthesizing results and examining those patterns in the environmental history-hominin evolution relationship that transcend individual locations or time intervals. The application of appropriate statistical techniques to infer trends and periodicities (Trauth et al., 2009) will be essential for the success of HSPDP, as will a vigorous modeling component to provide explanatory theory for understanding any potential climate-hominin evolution linkages that we uncover.

A drilling project focusing on human evolution in Africa offers unprecedented educational opportunities for communities near the drill sites, for educators, and for museums. The number of sites that might be drilled will provide welcome opportunities for research training for African geoscience students. Nontechnical outreach programs for local communities have proven successful for many drilling projects in the past (including at Lake Malawi in East Africa), and there was great enthusiasm at the meeting for developing a vigorous program along these lines for many different types of audiences. Because human evolution is a high profile target for scientific endeavors, many opportunities also exist for major museums to become involved in disseminating the results of HSPDP worldwide.

HSPDP opens up a new direction for scientific drilling. Although the focus of the immediate project is East Africa, the concept of developing synergies between the Earth science and paleoanthropology communities can (and almost certainly will) be applied worldwide, wherever the questions of relationships between human evolution and Earth system history arise. Future phases in such research might also involve collaborative ICDP/IODP efforts to collect new marine cores in critical locations and/or marine/terrestrial coring transects, as well as new drilling efforts on the extant and ancient deep rift lakes. "Drilling for human origins" promises to become an exciting new research direction in the years ahead.

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Rapid Response Fault Drilling Past, Present, and Future

by Emily E. Brodsky, Kuo-Fong Ma, Jim Mori, Demian M. Saffer, and the participants of the ICDP/SCEC International Workshop

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Introduction

New information about large earthquakes can be acquired by drilling into the fault zone quickly following a large seismic event. Specifically, we can learn about the levels of friction and strength of the fault which determine the dynamic rupture, monitor the healing process of the fault, record the stress changes that trigger aftershocks and capture important physical and chemical properties of the fault that control the rupture process. These scientific and associated technical issues were the focus of a three-day workshop on Rapid Response Fault Drilling: Past, Present, and Future, sponsored by the International Continental Scientific Drilling Program (ICDP) and the Southern California Earthquake Center (SCEC). The meeting drew together forty-four scientists representing ten countries in Tokyo, Japan during November 2008. The group discussed the scientific problems and how they could be addressed through rapid response drilling. Focused talks presented previous work on drilling after large earthquakes and in fault zones in general, as well as the state of the art of experimental techniques and measurement strategies. Detailed discussion weighed the tradeoffs between rapid drilling and the ability to satisfy a diverse range of scientific objectives. Plausible drilling sites and scenarios were evaluated. This is a shortened summary of the workshop report that discusses key scientific questions, measurement strategies, and recommendations. This report can provide a starting point for quickly mobilizing a drilling program following future large earthquakes. The full report can be seen at http://www.pmc.ucsc.edu/~rapid/.

Scientific Motivation

Scientists have long been asking questions about the physics of earthquakes in the hope that their catastrophic effects can somehow be mitigated. We can now generally delineate the regions where earthquakes are likely to occur. We can use seismic waves to measure the size and determine the location of an earthquake. We can model idealized ruptures and predict the resulting ground motions. We can design buildings that are resistant to the shaking near an earthquake. These advances have had direct benefits for the hundreds of million of people globally who are exposed to earthquake hazards.

However, further progress is largely hampered by a lack of fundamental data about the forces and processes on a fault deep beneath the ground during an earthquake. Knowing how much stress is exerted on the fault during slip is a prerequisite for predicting when the stress will break the fault and how far the fault will slip. We do not know how the fault evolves after an earthquake and how its changing structure resumes the strength required to generate more earthquakes. Even though aftershocks are one of the most predictable consequences of an earthquake, we do not understand the process that causes them. We also struggle to identify what aspects of fault geology separate seismogenic faults from faults that release stress by simply creeping. Immediately after a large earthquake, there is an opportunity to gain crucial information to fill these gaps in knowledge by observing the transient changes related to the rupture. For about two years, the fault is observably changed and a deep borehole can capture measurable signals germane to making progress in earthquake physics. Specifically, a deep borehole can address the following questions:

What Makes an Earthquake Big?

Earthquakes occur when the increasing local stress exceeds the frictional strength of a fault. A big earthquake occurs when the strength is pervasively low or the stress accumulation is high over a large region of the fault. Strain accumulation is relatively well understood and monitored through geodesy; however, the strength of faults and their time- and slip-dependence are much more poorly measured. At the large displacements and high velocities that characterize big earthquakes, even less is known about frictional strength, which may weaken dramatically during an earthquake. Understanding these currently unconstrained variations in frictional strength and their controlling mechanisms during large earthquakes is key to understanding the faulting process.

How Do Faults Heal for the Next Earthquake?

In the intervals between earthquakes, fault strength recovers slowly. Much of this process may not be measurable; however, recent work has shown that there is a window of opportunity after an earthquake when observable proxies for fault strength, such as seismic velocity, ground deformation, permeability, and aftershock rate, all change quickly (Brenguier et al., 2008; Kitagawa et al., 2002). Similarly, laboratory measurements document fault healing due to rate-and-state frictional and physicochemical processes, both of which evolve rapidly following slip (Hickman et al., 1995; Yasuhara et al., 2005). Scaling of laboratory observations to real faults is problematic but would be greatly aided by direct monitoring of a natural system.

How Do Earthquakes Interact?

Current data suggest that up to 80% of earthquakes are generally triggered by another earthquake (Marsan and Lengline, 2008). Some of these aftershocks themselves are large and damaging. However, while aftershocks are the most predictable earthquakes, we do not know if it is the dynamic stress of the seismic waves or the static stress change that activates the new earthquakes. How does stress change result in earthquakes that are delayed by weeks or months after the main shock? Determining the mechanism of triggered events is an important step on the road to earthquake prediction.

What are Important Material and Chemical Properties of the Seismogenic Zone?

Recent drilling projects on active faults show that fluids, mineralogy, and deformational structures all play important roles in fault behavior (Hickman et al., 1995; Ohtani et al., 2000; Ma et al., 2006). Specific combinations of these material properties may lead faults to episodically slip rapidly as opposed to gradually creep (Dixon and Moore, 2007). By sampling and instrumenting faults, we may be able to determine which combinations of properties lead to large ruptures. Furthermore, during healing following an earthquake, new surface area generated by fracturing is attacked by rapid chemical reactions that can destroy the original record of slip, so the sampling must be done before this process has advanced significantly.

How to Solve the Problems: What to Measure and Why

In order to learn about friction, healing, interaction, and nucleation, we need measurements of heat, stress, geological structures, frictional properties, permeability, seismic velocity, fluid chemistry, and local ground motion.

Temperature Measurements

Temperature profiles across the fault are the most direct way to quantify coseismic friction (Lachenbruch and Sass, 1980). Because most of the frictional resistance is dissipated as heat, any temperature increase on the fault at the time of the earthquake is potentially interpretable as a cumulative measure of frictional heat generation during slip. To measure the friction of an earthquake, the temperature must be measured in the vicinity of the seismogenic fault as quickly as possible and at depths where shear stress (a function of the effective normal stress and the effective coefficient of friction) is sufficiently large to generate an observable temperature anomaly (Fig. 1). The possibility of advection of frictionally generated heat by fluid flow following an earthquake must also be considered when interpreting downhole temperature data (Kano et al., 2006). Fulton et al. (2008) used a series of two-dimensional numerical models to simulate transient coupled fluid flow and heat transport to illustrate that temperatures across a fault zone should not be markedly affected by fluid flow driven away from the fault by locally elevated pore pressure (e.g., due to thermal pressurization or shear compaction). The results of these simulations illustrate that although the shape of a frictional heating anomaly will be modified if advective effects are substantial (e.g., in high-permeability cases), it would still be clearly resolvable after two years. Moreover, the use of repeated logging to monitor the evolution of thermal anomalies with time will allow separation of hydrologic (advective) and frictional heating signals.

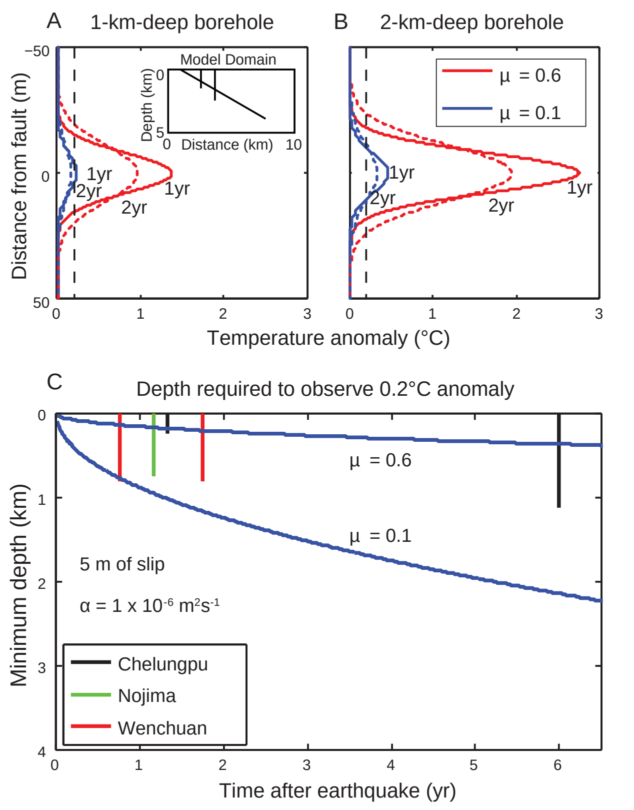

Figure 1. Frictional temperature anomalies resulting from a thrust earthquake with 5 m of slip and assuming a thermal diffusivity α of 10-6 m2s-1. (from Fulton et al., 2008) [A] Temperature anomaly for a borehole intersecting the fault at 1-km depth. Red and blue lines show frictional heating for effective friction coefficients of 0.6 and 0.1, representing strong and weak faults, respectively. Solid and dashed lines show the frictional heating anomaly one and two years after the earthquake, respectively. Dashed vertical black line shows the assumed detection threshold of 0.2°C. [B] Temperature anomaly for a borehole intersecting the fault at 2-km depth. [C] Blue lines show the minimum depth of borehole intersection with a fault to observe a temperature anomaly of 0.2°C as a function of time. The depth and timing of borehole completion of fault-zone drilling experiments are shown as vertical lines at the top of the panel [Figures from Fulton et al., 2008].

Direct Stress Measurements

An alternative approach to quantifying fault strength is to measure absolute stress directly. Determining the stress profile during rapid response fault-zone drilling, including the orientations and magnitudes of three-dimensional stresses, may tell us the stress change induced by fault rupture. Although it is difficult to estimate the magnitudes and orientations of three-dimensional stresses, the following quantities provide valuable information: vertical stress by downhole density logging, minimum horizontal stress by extended leak-off test/minifrac/hydraulic fracturing, and maximum horizontal stress by breakout width analyses (Zoback et al., 2003). A good complement to borehole data is core-based anelastic strain recovery (ASR) to produce complementary stress data (Lin et al., 2006). The longer the drilling is delayed, the more the stress will have decayed.

Geology of Cores

Some of the clearest evidence for the faulting process and frictional dissipation is preserved in fine-scale structures of cores. For instance, the presence of any melt rock (pseudotachylyte) is an immediate indicator of high friction early in the slip process, as heat is required to melt the rocks. Depending on the melt composition and permeability of the host, low friction during slip may be inferred later in the earthquake once melt has lubricated the surface. Geometric structures can also be used to assess the dynamic fluidization of the gouge and any likely rheology (Brodsky et al., 2009). If pseudotachylyte or fluidization structures are found, follow-up laboratory experiments are critical to determining the rheology of the melt or granular flow. Grain-size distribution also contains key information about dissipation. The energy that is absorbed in fracturing and surface creation is energy that is not dissipated by any other means, like friction. Similarly, measurements of fracture density in the borehole—using borehole imaging tools such as the Formation Micro Imager (FMI) and Resistivity-at-Bit (RAB)—and in the core itself constrain the dissipated energy, including that expended off the primary slip surface. Thus, observing the structure in a core provides some insight into frictional behavior. Fault-zone mineralogy changes rapidly during the healing process emphasizing the need for rapid sampling (Fig.2).

Laboratory Measurements

Most work on fault friction has been based on laboratory experiments on rocks sliding with limited velocities. However, unusual mineralogy, grain distribution, hydrological conditions, and structure in natural fault zones may significantly complicate the local frictional properties. Laboratory experiments can be manipulated to ascertain the exact effective stress and slip conditions to generate the observed stresses from the available materials. Furthermore, direct measurements of friction in the lab help to assess the applicability of the great body of rock mechanics to actual earthquake fault conditions. To diagnose the relative importance of various physical mechanisms during the earthquake, we must perform laboratory measurements of the frictional properties of gouge from the center of the fault zone (its core), and the results must be compared to the stresses inferred from the temperature and core-based stress measurements. Recent large-velocity experiments on natural gouge removed from fault cores show that significant weakening occurs as slip progresses (Tanikawa and Shimamoto, 2009).

Seismic Velocity

Seismic velocity has been shown to increase on a fault immediately after an earthquake (Li et al., 1998). A recent noise cross-correlation study showed velocity changes following the 2004 Parkfield earthquake that correlate with the slowly decaying strain transient (Brenguier et al., 2008). However, it is unclear if the seismic velocity change is an entirely shallow phenomenon or if it records a deeper process that is fundamental to the rheology of the fault; thus, measurements in a deep borehole are essential. Because changes often decay as 1/ time, measurements soon after an earthquake are important. Repeated vertical seismic profiles (VSPs) to measure velocity at depth in the nearfield of the fault could capture the progression of fault healing and changes in elastic moduli in the critical time period of the strong aftershock sequence. Borehole measurements should be supplemented with short-term surface deployments of short-period seismometers soon after the earthquake, with repeat deployments.

Hydrogeology

Dynamic fault-weakening mechanisms rely critically on the transient development of elevated (over ambient) pore fluid pressure via thermal or poro-elastic processes.

Figure 2. Slip lines observed on the slip surface of the Corinth core.

Permeability measurements in a fault zone are important in order to assess the sealing potential of the fault. The extent to which fluids may be trapped in a fault zone determines the shear stress during an earthquake and the locking strength before the next event. In addition, permeability can be treated as a proxy for fracturing and damage.

Permeability is known to evolve quickly after an earthquake rupture (Kitagawa et al., 2002). Pore pressure measurements are also important for evaluating static friction, since elevated pore pressure reduces the effective normal stress on faults and their overall shear strength (Rice, 1992). Preliminary interpretations based on drilling observations of the San Andreas Fault Observatory at Depth (SAFOD) (Zoback and Hickman, 2005) and the Chelungpu Fault in Taiwan (Doan et al., 2006) suggest that the fault zone is not overpressured at the depth where it is intersected by the borehole. These observations suggest that long-term weakening from high pore pressure may not be an adequate explanation for the apparent weakness of these fault zones.

Fluid Chemistry

Chemical precipitates close fractures and generate adhesion; therefore, the fluid chemistry must be sampled to develop a physical-chemical model of the healing process, and should include time series data from the fault core region (highly brecciated zone within the fault) as well as the damage zone. Real-time gas and hydrological monitoring will be critical for ascertaining the *in situ* chemical conditions.

What has been Learned from Prior Rapid Fault Zone Drilling Projects

Rapid drilling into a fault zone after an earthquake has already been done in the Nojima Fault, Japan, and the Chelungpu Fault, Taiwan. Future projects will build on this knowledge base. The full report also summarizes results from other fault zone drilling projects (SAFOD, Normal Aigion Fault in the Corinth Rift, Natural Earthquake Laboratory in South African Mines) that are not associated with recent large earthquakes.

Nojima Fault Drilling

Following the 1995 Kobe, Japan earthquake (Mw 6.9), the first rapid fault-drilling project was carried out on the Nojima Fault, which had surface rupture of about 1–2 m. Seven boreholes to depths of 500–1800 m were completed in fourteen months following the earthquake. Extensive geophysical measurements were made using standard logging techniques, along with borehole televiewer (BHTV), fullbore formation microimager (FMI), and dipole shear sonic imager (DSI) recordings. Resistivity, seismic velocity, and the various imaging techniques were useful for identifying fault zones and other physical properties throughout the drilled section. The borehole logging results were also correlated with the geological features of the core, such as fault gouge and cataclasites (Ikeda, 2001). Temperature measurements with relatively low resolution were made with the standard logging tools, but no signal associated with frictional heating was seen in the vicinity of the fault.

The boreholes provided nearly continuous core samples through the fault zone within granitic rocks and showed its complex geology. Distinct periods of seismic activity were recognized that were accompanied by intense hydrothermal alteration (Ohtani et al., 2000; Boullier et al., 2004; Tanaka et al., 2007). Ultracataclasites and pseudotachylytes that formed at 10-km depth or more were related to previous M6 to M7 earthquakes (Boullier et al., 2001; Murakami and Tagami, 2004). Estimates of the orientation of the local stress field were done with hydrofracturing and stress measurements on cores (Ikeda et al., 2001, Tsukahara et al., 2001; Yamamoto and Yabe, 2001). These stress direction studies showed that the maximum compressive stress was oriented nearly perpendicular to the fault, indicating low values for the static coefficient of friction.

Repeated water-injection experiments are being done in the 1800-m borehole to look for changes in fault permeability. Starting one year after the earthquake, and at subsequent intervals of a few years, water is pumped into the fault zone to induce small earthquakes. The timing and location of induced earthquakes, along with monitoring of resistivity, indicated permeabilities of 10^{-16} m^2 to 10^{-14} m^2 two years after the earthquake (Tadokoro, 2001). Subsequent injections suggest at least a 50% decrease in permeability over the subsequent three years (Kitagawa et al., 2002).

Taiwan Chelungpu Fault Drilling Project

An outstanding feature of the 1999 Chi-Chi, Taiwan earthquake (Mw 7.6) was the extensive surface rupture of the Chelungpu fault. The fault break was clearly visible for about 100 km, with surface displacements of 1–12 m. The regions of shallow slip provided the opportunity to access the seismogenic fault with drilling. The Taiwan Chelungpu Fault Drilling Project (TCDP) drilled two boreholes 40 m apart (completed 65 and 73 months after the earthquake) that penetrated the dipping thrust fault at depths of about one kilometer. The nearby surface fault had a displacement of about 12 m. There were also two shallow boreholes to depths of 330 m and 180 m on the northern and southern portions of the fault, respectively, which were completed 18 months after the earthquake (Tanaka et al., 2006).

The TCDP site near the town of Dakeng—where the earthquake had large displacement and slip velocity—was chosen in order to investigate the energy budget and the slip-weakening mechanisms of the earthquake (Ma et al., 2003). Identification of the fault zone in the core samples resulted from combining multiple techniques; they indicated a slip zone at 1111 m in Hole A and 1136 m in Hole B (Kuo et al., 2005; Ma et al., 2006; Hung et al., 2007; Sone et al., 2007; Yeh et al., 2007; Hirono et al., 2008). Evidence that the black gouge in these regions is in fact the slip surface comes from clay mineralogy, isotropic texture, absence of later reworking microstructures, and a very fine grain size indicative of high fracture energy in the Chi-Chi earthquake's energy budget (Ma et al., 2006).

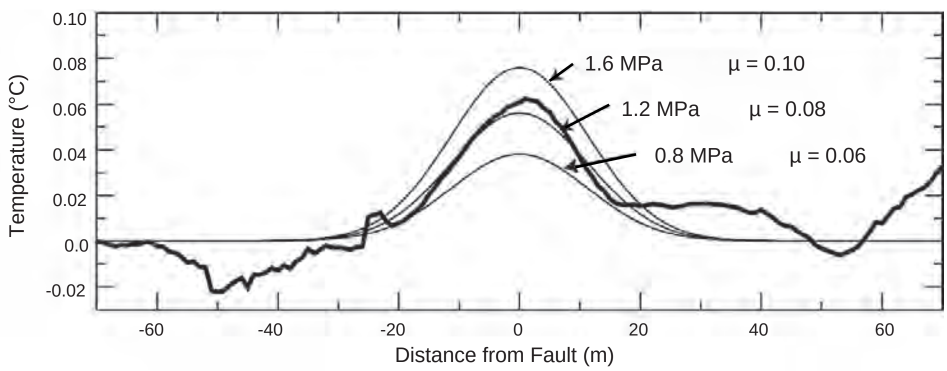

Figure 3. Temperature anomaly recorded in the Taiwan borehole and interpretation in terms of maximum friction coefficient (Kano et al., 2006).

Temperature measurements were made in the shallow and deep boreholes located in the northern region of large slip (Kano et al., 2006; Tanaka et al., 2006). Both studies found a consistent low level of residual heat close to the fault. In terms of frictional levels, these measurements imply a very low apparent coefficient of friction of around 0.1 to 0.2 (Fig. 3). Issues of water flow and determination of thermal diffusivity complicate the interpretation; however, these results show the potential importance of the temperature measurements at depth following a large earthquake.

Physical properties were measured continuously on cores using nondestructive methods (Hirono et al., 2007a). Clayclast aggregates and inverse grain size segregation were found in the Hole A principal slip zone and were interpreted as evidence for gouge fluidization as a result of frictional heating and thermal pressurization (Boutareaud et al., 2008; Boullier et al., 2009). Several other pieces of evidence—such as a magnetic susceptibility anomaly (Hirono et al., 2006; Mishima et al., 2006), clay mineralogy (Kuo et al., 2005; Hashimoto et al., 2008), whole-rock chemistry (Hirono et al., 2007b; Ishikawa et al., 2008), and gouge injections (Otsuki et al., 2005; Boullier et al., 2009)—show that the principal slip zone related to the Chi-Chi earthquake, as well as principal slip zones related to similar past earthquakes, have been heated to as much as 900°C and, consequently, are thermally pressurized and fluidized (Hirono et al., 2007b). Fluid circulation seems to be limited in the Chelungpu Fault, but healing processes and aseismic deformation by dissolution-diffusion-deposition mechanisms are important and efficient processes in the fault and damage zones (Boullier et al., 2009).

A cross-hole pumping test indicated a permeability of 10–16 m^2 to 10–18 m^2 along the fault, and simultaneous monitoring data suggested that the fault zone is moderately overpressured (Doan et al., 2006). Laboratory results on the shallow core samples show that the permeability of the northern region is an order of magnitude less than for the southern region (Tanikawa and Shimamoto, 2009).

TCDP samples have induced high international interest in friction experiments using soft rocks as initial material, and for slip-weakening processes in general. These studies have shown the lateral variability of the principal slip zone structure and thickness, along with the importance of clays and mineralogy of the gouge for slip weakening during coseismic slip. The analyses from FMI and DSI logging also indicate variations of the stress orientation near the principal slip zone, suggesting a complete stress drop during faulting with the exchange of the orientation of the SHmax to SHmin (Wu et al., 2007).

Wenchuan Fault Scientific Drilling Program

During the workshop, the Wenchuan Fault Scientific Drilling Program began drilling, with the first borehole begun only 178 days after the devastating Mw 7.9 earthquake in Sichuan, China on 12 May 2008. The project plans four deep holes through the faults in the Wenchuan region and represents one the most rapid drilling responses after an earthquake.

Proposed Earthquake Drilling Plan

Rapid drilling entails rapid decision making. Some of the discussion at the workshop centered on developing a drilling plan that can serve as a blueprint for future rapid response operations. All of the participants were cognizant of the variety of situations likely to be encountered in the real world and understood that no pre-earthquake drilling plan would be appropriate in detail for any particular situation. However, having a scenario plan that specifically addresses the key scientific questions helps provide a useful starting point for the work in the critical time following an earthquake.

Rapid response drilling should be considered whenever there is a large, on-land earthquake with sufficient surface slip (>1 m) to generate large geophysical and geological anomalies at depths accessible to a drilling program. The actual target earthquakes will probably be determined by the local scientific and technical infrastructure. Accessible onshore M≥7 earthquakes with at least 1 m of surface slip occur about every two to three years. The 1992 Landers, 1999 Izmit, 1999 Hector Mine, and 2002 Denali earthquakes would all have been appropriate targets, in addition to the 1995 Kobe, 1999 Chi-Chi, and 2008 Wenchuan earthquakes. Workshop participants reported on likely scenarios in China, Iran, Japan, New Zealand, Turkey, and the United States. Several of these countries already have fault zone drilling programs underway that could be accelerated and adapted when a large earthquake occurs.

For the plan, several basic selection requirements for drilling sites are aimed at addressing fundamental questions about earthquake energy budgets and fault zone processes. First, it is desirable to drill where the fault and regional geologic structure are well-known and relatively simple. A single major fault strand rather than multiple active traces will provide data that are more easily interpretable in the context of seismological information. Second, drilling should target a region of high co-seismic slip on the fault, as defined by seismological inversions and surface deformation data. Slip should be at least 1 m in order to ensure a measurable frictional signal. Ideally, the drilling would reach nucleation depths, although this is unlikely to be feasible in many cases, and thus most drilling projects will concentrate on the problems of friction, healing, and earthquake interaction. Third, crystalline rock is preferred over sedimentary rock because of its low permeability and its well-defined frictional properties. Unconsolidated sediments are particularly problematic for studying the seismogenic zone. Fourth, a dipping fault is ideal (though not required) because it would allow crossing the fault at a high angle with a vertical borehole. This scenario drilling plan assumes a dipping fault. Finally, it would be desirable to drill in a location where there are numerous pre-existing seismological and GPS stations, to provide additional needed information about the earthquake.

A significant challenge in designing and implementing a drilling plan is coordination of multiple downhole measurements and instrument installations, due to competition for limited space in the hole and potential interference. Multiple objectives must be spatially and temporally balanced, requiring care in the following: (a) design and completion strategy, including planning of measurement sequences to minimize interference; and (b) prioritization and compromise of some measurements (e.g., running only low volume perturbation tests for stress and hydrologic measurement objectives, or conducting only limited coring). Key observations of temperature logging, seismometers and strainmeters, hydrologic testing, and fluid sampling, all have specific hole configuration and/or timing requirements that are often conflicting.

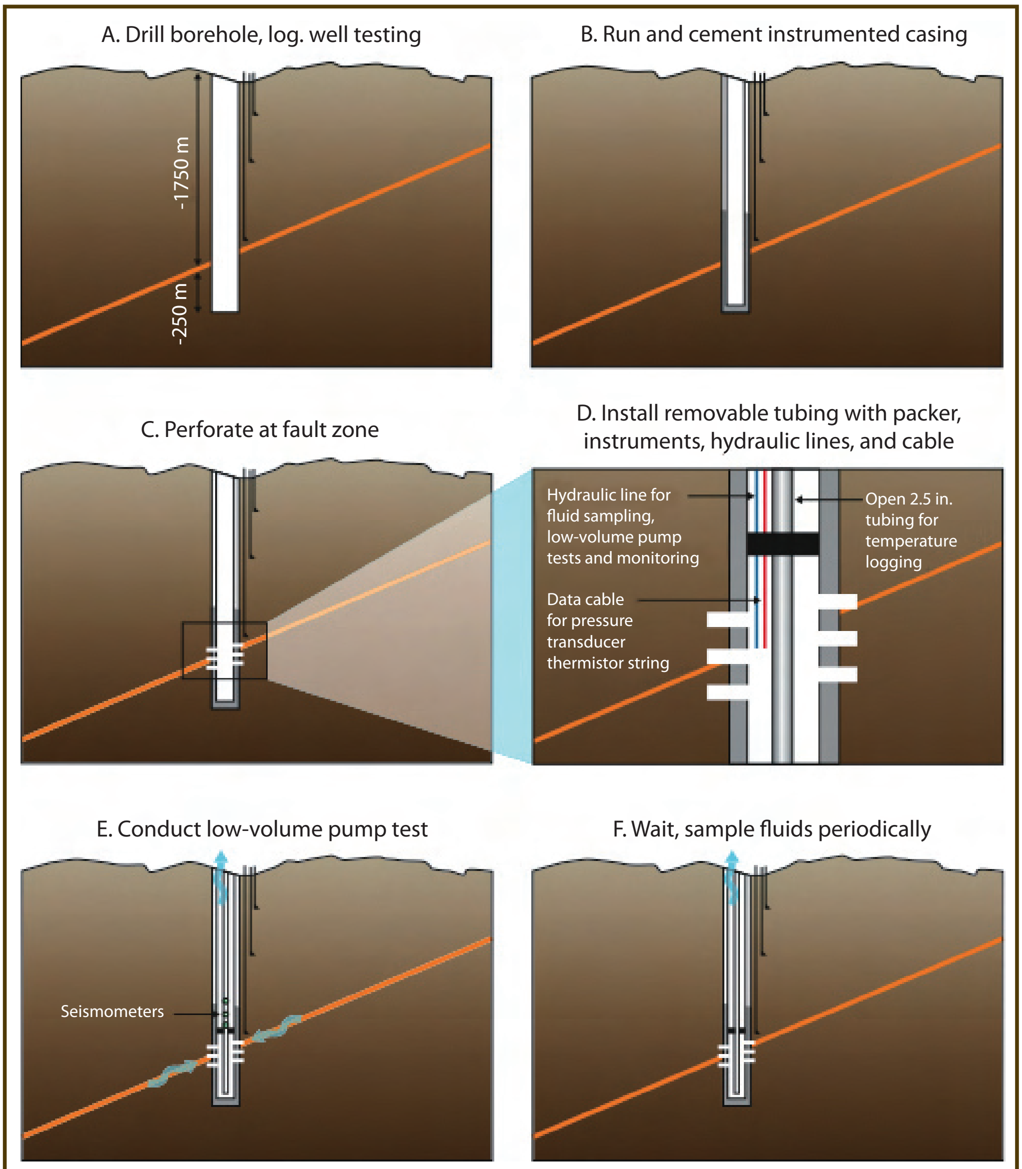

Figure 4. Schematic of a rapid drilling plan.

We provide a sample drilling plan (Fig. 4) to illustrate how to balance competing measurements in a realistic scenario. One key consideration is the minimum target depth required to obtain meaningful information about frictional heating, given instrument resolution and the magnitude of the expected thermal anomaly (based on average shear stress and the total amount of slip). There is a tradeoff between these considerations and the amount of time needed for drilling. For a suite of conservative assumptions about heat generation, a 2-km-deep hole drilled within six to twelve months following an earthquake is sufficient; deeper drilling is better, but the time and cost increase exponentially with increased depth. This depth range is also adequate for the desired geophysical measurements. This scenario drilling plan shows a 2-km-deep hole, penetrating a fault at 1750-m vertical depth. This plan and general completion strategy could be adjusted for any target fault depth, although the details of casing set points and sizes would need to be modified.

Recommendations

The key recommendation of the workshop is that rapid drilling should be a priority of the international drilling community following on-land earthquakes that occur with more than 1 m of slip in regions with sufficient infrastructure to support the technical operations. The optimal drill site is on crystalline rock with a dipping fault and well-characterized geology. The hole should be initiated within six months after the earthquake and should be drilled to a depth of at least 2 km.

To achieve this goal, the workshop participants recommend the following courses of action for ICDP and the scientific community (listed separately).

Recommendations for ICDP

- ICDP should form a standing committee on fault drilling.
- A mechanism should be created to facilitate rapid evaluation and funding of scientific drilling proposals immediately following an earthquake.
- Fault zone drilling projects should include a contingency plan for accelerating or reconfiguring the project in case of a major earthquake.
- An inventory of baseline data on and near major faults should be constructed under the supervision of the standing committee as soon as possible for reference information before an earthquake occurs. The inventory should include existing, accessible boreholes, current seismological and geodetic instrumentation, and paleoseismic constraints. As part of this process, geophysical logging should be conducted on extant boreholes in strategic locations near major faults.
- An emergency response kit should be built and maintained by ICDP, including material stockpiles and borehole instrumentation and including special downhole tools.
- Investments should be made into developing and improving sensors for deep, hot adverse fault zone environments.

Recommendations for the Scientific Community

- National and regional groups should form and work on scenario plans for their localities. Clear and accurate geological and geophysical information prior to a major earthquake are critical for optimally selecting a study site after the earthquake.
- Complementary seismological and geological studies at potential sites of large earthquakes should be undertaken. Existing boreholes should be logged. These baseline data are critical to post-earthquake interpretations.

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Deep Fault Drilling Project—Alpine Fault, New Zealand

by John Townend, Rupert Sutherland, and Virginia Toy

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The Alpine Fault, South Island, New Zealand, constitutes a globally significant natural laboratory for research into how active plate-bounding continental faults work and, in particular, how rocks exposed at the surface today relate to deep-seated processes of tectonic deformation, seismogenesis, and mineralization. The along-strike homogeneity of the hanging wall, rapid rate of dextral-reverse slip on an inclined fault plane, and relatively shallow depths to mechanical and chemical transitions make the Alpine Fault and the broader South Island plate boundary an important international site for multi-disciplinary research and a realistic target for an ambitious long-term program of scientific drilling investigations.

Introduction

The mid-crust is the locus of several fundamental geological and geophysical phenomena. These include the transitions from brittle to ductile behavior and from unstable to stable frictional sliding; earthquake nucleation and predominant moment release; the peak in the crustal stress envelope; the transition from predominantly cataclastic to mylonitic fault rocks; and mineralization associated with fracture permeability. Current understanding of faulting, seismogenesis, and mineralization in this tectonically important zone is largely based on remote geophysical observations of active faults and direct geological observations of fossil faults.

The Alpine Fault, New Zealand, is a major dextral-reverse fault that is thought to fail in large earthquakes (M_w ~7.9) every 200–400 years and to have last ruptured in the year 1717. Ongoing uplift has rapidly exhumed a crustal section from depths of as much as 30 km, yielding a young (<~1Ma), well-preserved sample of mid-crustal structures comparable to those currently active at depth. Surface studies and geophysical experiments have provided valuable images of structures and associated deformation mechanisms, and contributed to archetypal models of continental faulting and orogenesis.

An International Continental Scientific Drilling Program-funded workshop attended by sixty-one researchers from seven countries was held on 22–28 March 2009 at Franz Josef, adjacent to the central portion of the Alpine Fault. The workshop addressed the state of knowledge of the Alpine Fault; the significance and feasibility of a multi-national program of drilling and allied science; and the preliminary steps required for site characterization, preparatory drilling, and longer-term science planning. The program involved seventeen technical presentations on the Alpine Fault, earthquake physics and faulting, and scientific drilling, as well as fourteen talks addressing related subjects and intended to stimulate discussion. The program also contained field trips to sites along the Alpine Fault to view fault rocks and geomorphic features as well as potential drill sites.

Three principal scientific themes emerged from the workshop: (1) evolution of a transpressive orogenic system; (2) ductile and brittle deformation mechanisms, and their interaction; and (3) seismogenesis and the habitat of earthquakes. The remarkable along-strike homogeneity of the Alpine Fault's hanging wall, the rapid rate of slip, and the dextral-reverse kinematics enable the progressive evolution of fault zone materials to be examined by linking rocks exposed at the surface to their *in situ* protoliths at depth along common exhumation trajectories. In the central portion of the fault, where exhumation rates and thermal gradients are highest,

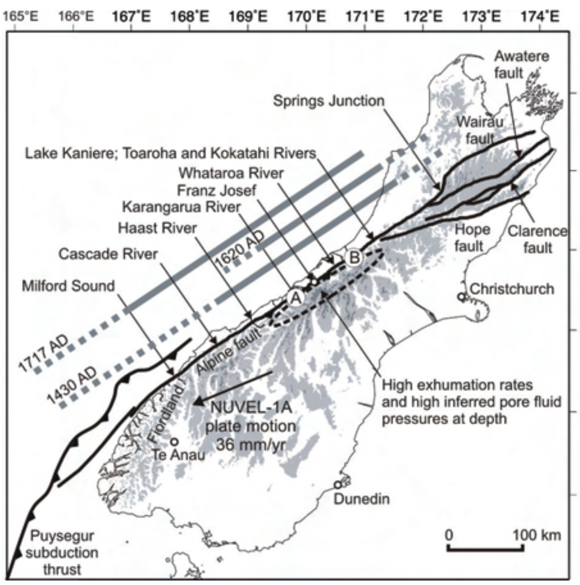

Figure 1. Map of the South Island of New Zealand showing principal features of the Australia–Pacific plate boundary and key locations referred to in the text. "A" and "B" mark the ends of the along-fault illustration in Fig. 4. The thick gray lines indicate the inferred extent of past Alpine Fault ruptures during historical times. Light gray shading demarcates topography higher than 800 m. Reproduced by permission of the American Geophysical Union after Sutherland et al., 2007. Copyright 2007 American Geophysical Union.

several sites can be identified at which rocks encountered at depth in boreholes would correspond to well-studied outcrops, enabling progressive geological deformation and petrological changes to be studied as functions of space and time along the transport path.

The Alpine Fault affords a rare opportunity to study, via scientific drilling and allied research, the physical character of tectonic deformation at depth within a major active continental fault that is late in its seismic cycle and which can be geophysically monitored in the coming decades.

Tectonic Setting

The Alpine Fault is the primary structure accommodating Australia–Pacific plate motion in New Zealand's South Island (Norris et al., 1990; Fig. 1). It is a mature dextral-reverse fault that offsets basement rocks laterally by ~470 km, with estimated late Quaternary horizontal displacement rates of 21–27 mm yr^{-1} (Wellman, 1953; Norris and Cooper, 2001; Sutherland et al., 2006). Paleoseismic evidence near the Alpine Fault identifies earthquakes in the years 1717, 1620, and 1430, with estimated moment magnitudes of 7.9±0.3, 7.6±0.3, and 7.9±0.4, respectively (Sutherland et al., 2007).

In the central South Island, the Alpine Fault is dextral-reverse and bounds the western edge of the Southern Alps (Norris et al., 1990). Rapid exhumation (~6–9 mm yr^{-1}; Little et al., 2005) has also produced rapid cooling, indicated by decreasing metamorphic grade and increasing thermochronological age with distance from the fault (Koons, 1987; Batt et al., 2004; Little et al., 2005). It has produced a spectacular exposure of the crustal section from depths of as much as 20–30 km (Little et al., 2002; Norris and Cooper, 2003). The exposed section may provide a young proxy for material currently deforming at mid-crustal depths, allowing unprecedented ground-truthing of geophysical data and the interpretation of borehole observations in terms of recent fault products—and *vice versa*.

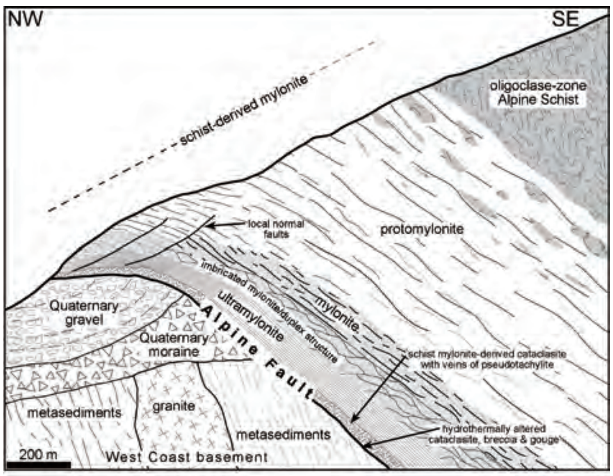

Figure 2. Schematic cross-section of an oblique thrust segment within the central section of the Alpine Fault. Reproduced by permission of the American Geophysical Union after Norris and Cooper, 2007. Copyright 2007 American Geophysical Union.

The exhumed 1–2-km-wide Plio-Pleistocene mylonite zone (illustrated schematically in Fig. 2) demonstrates that localized deformation occurs beneath the brittle part of the Alpine Fault (Sibson et al., 1979; Norris and Cooper, 2001, 2003; Toy et al., 2008 and references therein). Along its central segment, the fault juxtaposes a hanging wall of lithologically rather uniform high-grade (up to garnet-oligoclase facies) foliated Alpine schists against a footwall comprising a basement of Paleozoic greywackes (Greenland Group) intruded by Devonian–Cretaceous granites and overlain by a Cretaceous–Cenozoic cover sequence (see Cox and Barrel, 2007; Cox and Sutherland, 2007). Although portions of the fault zone are exposed in numerous river sections, no exposed complete fault-rock sequence from hard-rock hanging wall to hard-rock footwall has yet been located.

About 7 km structurally above the Alpine Fault lies a brittle-ductile shear array inferred to have formed at >20-km depths, with evidence for complex, transient semi-brittle behavior at high strain-rates and fluid pressure cycling on relatively short, possibly seismic, timescales (Wightman and Little, 2007). The base of the hanging wall seismogenic zone inferred from contemporary seismicity is relatively shallow (~8–12 km; Leitner et al., 2001). Geodetic studies are consistent with a shallow (5–10 km) depth for full fault locking (Beavan et al., 1999), though some degree of interseismic coupling may persist to as deep as ~18 km (Wallace et al., 2007). In the mid-crust, the fault zone exhibits low seismic wave speeds and high attenuation (Stern et al., 2001; Eberhart-Phillips and Bannister, 2002; Stern et al., 2007 and references therein) and high electrical conductivity (Wannamaker et al., 2002), suggesting interconnected saline fluids at high pressures within the ductile regime.

Why the Alpine Fault?

The Alpine Fault is a well-studied active continental fault that, unlike many other similar faults elsewhere, has not produced large earthquakes or measureable creep in historic times; however, paleoseismic data suggest that it has produced large earthquakes in the Holocene and that it is late in the earthquake cycle. The Alpine Fault's dextral-reverse kinematics, non-vertical dip, and rapid slip rates have exhumed to the ground surface a fresh sample of fault rocks inferred to have formed at depths of as much as 30 km within the last few million years. Due to its relatively steep dip, fluid-saturated state, and high near-surface geothermal gradient, the Alpine Fault serves further as an analogue for environments in which economically significant mesothermal mineralization has occurred (Koons and Craw, 1991; Weinberg et al., 2005; Sibson, 2007).

The following factors and related logistical considerations make the Alpine Fault a globally significant target of fundamental research into tectonic deformation, seismic hazard, and mineral resource formation:

- The >300-km along-strike exposure of a relatively uniform-lithology hanging wall and derived fault rocks that formed during the current tectonic regime, providing an exceptional reference for interpreting observations of contemporary processes and structure and older, exhumed structure
- Rapid uplift resulting in advection of crustal isotherms so that brittle-ductile transition processes can be studied at shallower depths than possible in other active transpressional settings
- Sequences of fault rocks developed during unidirectional exhumation on well-determined trajectories over relatively short time periods
- The opportunity to study on an ongoing basis the state of a locked fault thought to be late in the earthquake cycle
- Well-determined, rapid Quaternary slip rates
- An extensive body of geological and geophysical knowledge, and a modern, nationwide geophysical monitoring network (GeoNet; Fig. 3)
- A non-vertical fault orientation enabling fault penetration with either subvertical or incline holes
- A relatively benign political and physical environment in which to operate with existing petroleum industry onshore drilling activity and supporting infrastructure.

Why Drill?

Drawing inferences about conditions and processes prevailing at seismogenic or greater depths based on outcrop observations is complicated by the fact that rocks exposed at the surface may have undergone modifications—structural, mineralogical, and geochemical—during their exhumation and at shallow depths.

One way of examining and accounting for the character and extent of upper crustal modifications is to examine a rock mass at depth whose future exhumation trajectory intersects a present-day surface outcrop (i.e., to treat the rock mass at depth as the protolith of the modified rocks now observed at the surface). The Alpine Fault kinematics are such that fault rocks evolve progressively on a path towards the surface, where they exit the system. This allows examination of progressive fault rock development using paired borehole and surface observations that is not possible on purely strike-slip faults where fault rocks may be continuously reworked at the same depth throughout the fault's history.

The second principal reason for drilling into the central Alpine Fault is to address the physics of faulting and seismogenesis by gaining access to the fault zone at depth and determining the temperature, fluid pressure and chemistry, bulk rock properties, and stress conditions prevailing at a late stage in the earthquake cycle, and establishing a long-term monitoring capability. Drilling enables continuous observations to be made of the fault zone in the immediate vicinity of the borehole itself and further afield using fault-zone guided waves, for instance (Li and Malin, 2008). It also provides a mechanism of calibrating and interpreting remote observations, such as those provided by the South Island Geophysical Transect project (SIGHT; Okaya et al., 2002; Stern et al., 2007), and linking these to surface data and rupture models. Laboratory measurements made on samples retrieved from depth, as well as measurements of the conditions under which those samples were collected, are required to more accurately describe the physical characteristics of fault rocks during coseismic rupture, and to account for strong ground motions (Beeler, 2006; Rice and Cocco, 2007).

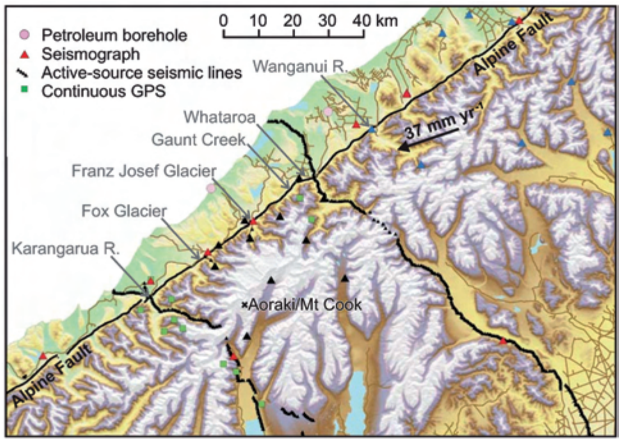

Figure 3. Map of the central section of the Alpine Fault showing existing infrastructure, the onshore portions of the South Island Geophysical Transect (SIGHT) active-source seismic lines, background seismicity, and the locations of possible drill sites.

Figure 4 illustrates the idealized geometry of the Alpine Fault in the central Southern Alps (inset stereogram) and a schematic view of the fault plane (as viewed normal to the plane), with the locations of key surface outcrops and fault-crossing roads marked. The regional fault plane strikes northeast and dips at approximately 50° to the southeast on

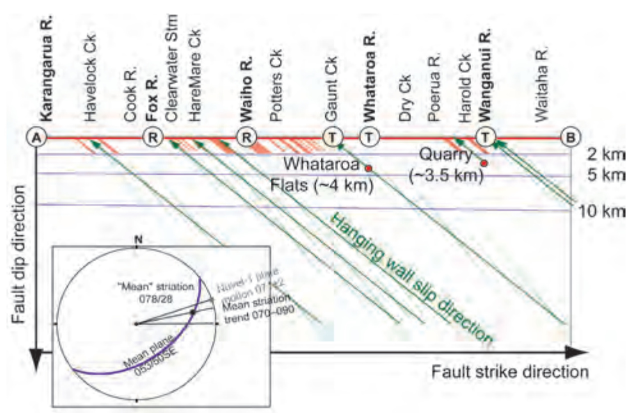

Figure 4. Schematic view normal to the mean fault plane in the central Alpine Fault region showing rock uplift trajectories and key outcrop locations. Place names shown in bold correspond to prospective drill sites. "A" (southwest) and "B" (northeast) are marked on Figure 1 for reference. "T" and "R" denote tracks and roads, respectively, crossing the fault trace. The short red lines mark strike-slip sections of the fault trace. The inset summarizes the mean fault geometry in stereographic projection.

average, and northeast-plunging striations define a mean rake of ~38° NE (Norris and Cooper, 1995; 1997; Little et al., 2002). Figure 4 demonstrates that there are several points along the fault at which several kilometers' access to the hanging wall is possible northeast of known surface outcrops. This means, for example, that a vertical borehole drilled approximately 3.5 km southeast of where the Alpine Fault crosses the Whataroa River would intersect the Alpine Fault at a depth of ~4 km, sampling material expected to breach the surface in ~0.4 Myr. Most importantly, however, the point at which the borehole intersected the fault plane would lie on the exhumation trajectory of the rocks now exposed in the Gaunt Creek outcrop.

Key Discussion Points

During the course of the workshop, three principal scientific themes and associated research goals emerged:

1. *Evolution of an orogenic system*—to determine how an active transpressional plate boundary system interacts with climate, landscape, and hydrological and thermal regimes;
2. *Ductile and brittle deformation mechanisms*—to determine via integrated surface and borehole observations what deformation mechanisms, mineralogical processes and conditions characterize the ductile and brittle regimes, and their interaction;
3. *Seismogenesis and the habitat of earthquakes*—to examine a major, locked, late-stage, continental fault at depth, determine the conditions under which earthquakes occur, and characterize the materials within which ruptures propagate.

The accompanying group discussions identified a number of common scientific issues related to the Alpine Fault and major continental faults in general, which are summarized below.

Ambient Conditions

A key theme to emerge from the group discussions was the vital importance of understanding the thermal and fluid flow regimes surrounding the Alpine Fault. Current thermal and hydrological models of the shallow to mid-crust in the vicinity of the Alpine Fault, particularly on the hanging wall, are limited by sparse data and consequent uncertainties in the maximum depth and pattern of topographically-induced fluid flow, the permeability structure, and shear heating effects.

The present-day shallow thermal regime west of the Alpine Fault can be inferred from petroleum exploration wells (Townend, 1999), but data are scarce in the immediate vicinity of the Alpine Fault's surface trace and further east. Models of the thermal structure of the Southern Alps orogen (Koons, 1987; Allis and Shi, 1995; Upton et al., 1995; Batt and Braun, 1999; Gerbault et al., 2003) differ quite markedly, and further work is required to reconcile these models with geodetic and seismological estimates of interseismic locking depths and the seismogenic thickness.

Temperature, fluid pressure and chemistry, and stress are all likely to be strongly perturbed at shallow depths by the pronounced topographic relief (as is the Alpine Fault's shallow structure itself; see below) and to differ more markedly from conditions prevailing at depth than has been the case in active fault drilling experiments elsewhere (Zoback et al., 2007). Detailed modeling of all three fields to determine how deep these effects persist is a high priority as plans for future drilling evolve.

Fluid and Rock Geochemistry

The full armory of elemental and isotopic techniques has yet to be brought to bear on fluids sampled in hot springs emanating from around the fault and trapped in exhumed veins within the fault zone and hanging wall. It is likely that more complete suites of geochemical data will aid the identification of fluid sources and flow-paths (Upton et al., 1995; Koons et al., 1998), and in particular enable more detailed analysis of progressive fluid-rock interaction. Among the outstanding questions related to fluid discharge are those of what factors control the number of hot springs along the Alpine Fault, their temperatures (<56°C), and the apparent gap in springs between the Cascade and Karangarua Rivers.

Alpine Fault Geometry

Key to the viability of any future drilling operations is improved knowledge of the Alpine Fault's shallow geometry. Seismic data indicate that the fault has a listric structure in the mid- and lower crust, with its southeastward dips decreasing from ~60° at 15 km depth to ~40° at 25 km depth and to almost zero at 30 km (Stern et al., 2007, and references therein). However, the fault's orientation at depths of hundreds of meters to several kilometers is still poorly constrained. Moreover, the central Alpine Fault (between Whataroa and Haast) exhibits "serial partitioning" into oblique thrust and strike-slip segments whose along-strike dimensions (typically <3 km) appear to be controlled by the spacing of major rivers (Norris and Cooper, 1995, 1997). Erosional control on the segmentation suggests that the segments likely merge into a single oblique structure at depths comparable to the topographic relief (~1000–1500 m), but detailed geophysical work is required to image these near-surface structures and determine their geometries at the depths that drilling might target.

Fault Zone Structure

Prevailing models of Alpine Fault zone structure at various depths have been compiled from partial data sets collected at different locations along the surface trace and in the hanging wall (Reid, 1964; Sibson et al., 1979; Sibson et al., 1981; Norris and Cooper, 1995, 1997, 2003, and 2007; Warr et al., 2007; Toy et al., 2008). Deconvolving near-surface or retrogressive effects that develop in response to depressurization, cooling, and interaction with progressively cooler fluids, from those resulting from cataclastic processes and frictional melting during deeper deformation (Warr and Cox, 2001) will be aided by analysis of suites of petrological and structural observations made at different depths along a single exhumation trajectory. Furthermore, borehole measurements are expected to provide information about changes in fault zone geometry and hence strain distribution, at different depths within the brittle and ductile regimes.

Seismogenesis and the Habitat of Continental Earthquakes

The Alpine Fault provides an excellent opportunity for elucidating the rheological properties and constitutive responses of real fault materials and host rocks. The overall mechanical behavior of a fault zone is likely to be controlled coseismically by thermal and hydraulic factors as well as the fault zone's intrinsic structure. Understanding the short- and long-term evolution of fault microstructures and fault zone fluids, their interaction and their temporal evolution should provide new insight into what mechanisms govern rupture propagation and termination (Sibson, 1985; Wesnousky, 2006; Rice and Cocco, 2007). Comparisons of fault rocks now exposed at the surface with samples retrieved from progressively greater depths and coincident measurements of *in situ* stress, fluid pressure, permeability, and elastic parameters would inform laboratory experiments and theoretical modeling. These issues provide a vital link between detailed structural and microstructural studies of fault rocks and rupture physics-based models of seismic radiation, strong ground motion, and transient interseismic processes. Further, they bear directly on questions of what governs the transition between brittle and ductile deformation processes, the generation and significance of pseudotachylytes, and the mechanical characteristics of a locked fault posing a major seismic hazard.

Interaction between Brittle and Ductile Deformation Processes

The transition in both space and time between continuous, temperature-controlled creep deformation at depth and episodic, pressure-sensitive frictional sliding in the upper-crust (commonly although controversially referred to as the "brittle–ductile transition") is fundamental to understanding the mechanics of crustal scale faults (Rutter, 1986). Characterizing this transition relies on being able to distinguish different grain-scale deformation mechanisms in samples of fault rocks, and determining the effects on those mechanisms of strain rate, temperature, pressure, and fluids (chemically and physically; e.g., Craw and Campbell, 2004).

Interaction of Climate, Landscape, and Tectonics

A great deal of scientific attention has focused on the role of tectonic processes in altering the Earth's topography and, more recently, the effects of surface processes on fault behavior (Koons and Kirby, 2007). The Alpine Fault is unusual in that it currently accommodates fault-parallel and fault-normal displacements on a single dipping structure (Norris et al., 1990; Stern et al., 2000). This has been suggested to reflect thermal weakening resulting from the highly asymmetric precipitation and erosion patterns of the Southern Alps (Koons et al., 2003) and serves as one example of the influence that orographic effects may exert on deep-seated faulting behavior (Upton et al., 2003, 2009). Better understanding of the rates and spatial variations in exhumation are required to more fully investigate climatic and physiographic effects on faulting.

Site Selection and Survey

Scientific Criteria

The key scientific factors that render the Alpine Fault a globally important focus for drilling—geometry, kinematics, rates, exposure—mean that the area of most relevance to drilling is the central section of the fault, between the Karangarua and Wanganui Rivers (Fig. 4), where dip-slip rates on the Alpine Fault and hanging wall exhumation rates are greatest. The central section is approximately bounded by the two longest deep-crustal seismic transects studied during the SIGHT project, providing the opportunity to tie various borehole observations to deeper remote measurements.

The key scientific criteria to be considered, therefore, are as follows: scientific relevance, representativeness, and significance; location in the central segment of the Alpine Fault; scope for multiple boreholes at different distances from the fault; and opportunities for aligned research.

Logistical Criteria

Much of the Alpine Fault lies within a region of very high conservation value; indeed, the central segment of the fault is also the area of highest conservation significance. Hence, one key logistical constraint on drilling operations and related surface studies is the need to minimize environmental impact within a high-profile conservation estate.

Steep topography, high rainfall, and active erosion make access to the hanging wall difficult (in fact, only three graded roads extend more than 1 km east of the fault trace in the central region of most rapid uplift), and field conditions are often challenging. In evaluating different potential drill sites, consideration of the following logistical factors will be particularly important: physical access to the hanging wall; permitting requirements; site conditions (e.g., vulnerability to flooding, ground stability); and visibility/impact.

Sites under Consideration

Figure 4 illustrates the five locations in the central segment of the Alpine fault where roads or farm tracks extend more than 1 km into the hanging wall. Also marked are five locations provisionally identified as possible drill sites requiring detailed site characterization studies—the Wanganui, Whataroa, Waiho (Franz Josef), Fox, and Karangarua River valleys. Of these sites, only the Wanganui, Whataroa, Waiho, and Karangarua River locations are closely linked to known surface outcrops along exhumation trajectories. The Waiho, Fox, and Karangarua Rivers are located in high-profile conservation areas, while the Wanganui River is somewhat removed from the northern SIGHT transect and the zone of most rapid uplift.

The experiment outlined here is well-suited to a multi-phase drilling program conducted over several years and involving a number of boreholes accompanied by detailed local and regional surveys and commencing with shallow (50–150-m-deep) core characterization and instrumentation holes and 1–2-km-deep exploratory holes, and going progressively deeper. This would enable the final and technologically most challenging phases of drilling and monitoring to be directly informed by sub-surface measurements in a similar manner to that used in projects elsewhere.

Surveys Required to Characterize and Define Drilling Targets

In order to adequately evaluate the suitability of any particular site for a long-term drilling operation, it will be necessary to conduct a coordinated multi-disciplinary site characterization program at each site. This program will focus on better defining the geometry of the fault and near-surface units, including alluvium; engineering site design, taking into account flood and landslide hazards; borehole design and stability analysis; and borehole instrumentation planning.

To take maximum advantage of downhole measurements and samples, a large program of aligned research that puts drilling results in context will be conducted. Some of this aligned research is being undertaken already (e.g., detailed geological and geomorphological mapping; paleoseismology; fault rock petrography and geochemistry; local seismicity analysis and tomography; active source seismic studies; numerical modeling). Other techniques (e.g., fault-zone guided wave studies; multi-system thermochronology; laboratory rock mechanics; permeability measurements; analysis of core retrieved from shallow boreholes) have yet to be fully applied to the Alpine Fault and will provide essential data for planning future deep boreholes.

Immediate Actions

Three working groups were convened at the March 2009 workshop to undertake preliminary studies in site selection and characterization, shallow drilling for core characterization and technical feasibility tests, and hydrogeological and thermal modeling and sampling. A fourth group will be convened in late 2009 to review and develop sampling protocols and coordinate permitting and funding applications.

The anisotropic, steeply-dipping fabrics of the hanging-wall Alpine Schist and the Alpine Fault mylonites may pose technical obstacles to drilling. Planning has commenced for a pilot drilling program, likely to take place in the 2010/2011 austral summer, during which one or more shallow (~50–150-m-deep) boreholes will be drilled using a mining rig to evaluate technical configurations, retrieve unweathered core from the fault zone, and conduct downhole logging in conjunction with surface measurements.

Ongoing programs of hot spring monitoring will be extended in 2010 with measurements of shallow subsurface flow and permeability in tunnels transecting the Alpine Fault hanging wall, and hot spring gas chemistry experiments. Temporary seismograph arrays currently deployed north and south of the Whataroa River will be augmented in 2010 to ensure that along-strike variations in seismicity near the Wanganui and Whataroa River prospective drill sites are recorded with a relatively homogeneous network with average instrument spacings of ~5 km. Planning will also begin for a higher-density (~1-km-spacing) transportable array with which to resolve fine-scale structures at each potential drill site in conjunction with active-source studies.

To facilitate the scientific and logistical activities, all activities will be coordinated via the project website (http://drill.gns.cri.nz/nzcdp/dfdp/), where up-to-date information regarding the working groups and the site characterization program may be found.

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Related Web Links

http://drill.gns.cri.nz/nzcdp/dfdp/index.html
http://www.icdp-online.org

The ESF Magellan Workshop

"Beyond 2013—The Future of European Scientific Drilling Research", convened by G. Camoin, R. Stein, and M. Wagreich, was held at the Geocenter, University of Vienna, Austria on 24–25 April. Its main objectives were to define and document the European interests in an international scientific drilling program beyond 2013, and to prepare the INVEST Conference (Bremen, Germany, 23–25 September 2009). Eighty scientists from sixteen countries and from various expertise attended the workshop, which included general sessions and breakout group discussions. The topics that were discussed during the workshop included (1) the future of ECORD and IODP; (2) the new research initiatives and emerging fields in scientific drilling; (3) the relationships between IODP and other programs, and the collaboration between academia and industry; and (4) new technologies and the Mission Specific Platform approach. The major outcomes of the workshop and outlooks will be summarized in a white paper on the Future of European Ocean Drilling Research that will be edited prior to the INVEST Conference.

"Smart-Plug" Packer Systems Used for NanTroSEIZE

The multi-expedition IODP Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) will complete a transect of holes drilled through the Nankai accretionary prism. Coring, logging, and long-term monitoring experiments conducted in these drill holes will reach faults and wall rock at various depths, including the seismogenic part of the subduction thrust fault. During Stage 2 operations (*DV Chikyu* Expeditions 319 and 322), two holes will be drilled and cased along the transect in July–August 2009 to prepare for later installation of CORK observatories. To make use of these holes during the time between drilling and final CORK installation, a group of Canadian, U.S., German, and Japanese scientists have designed and built temporary "Smart-plug" packer systems to record formation pressures and temperatures. The data will document ambient conditions and provide proxies for strain and fluid flow related to tectonic and seismic activity. During NanTroSEIZE Stage 3, the "Smart-plugs" will be recovered and replaced by the permanent CORK observatories, and will ultimately be connected to the seafloor fiber-optic cable network DONET. These observatories will include seismometers, strain meters, thermistors, and pressure sensors.

Assembly of the interior of the "Smart-plug" (left); Smart-plug housing (center, with L-R: Martin Heesemann (University of Bremen), Bob Meldrum (Pacific Geoscience Center), Demian Saffer (Penn State University), Earl Davis and Bob Macdonald (both PGC).

Message from New President of IODP-MI, Dr. Kiyoshi Suyehiro

In my new role as IODP-MI President, I first would like to congratulate all the dedicated people who have contributed in many different ways bringing IODP to its current level of operations, achievement, and international regard. We have embarked on a truly unique international scientific undertaking and must continue to deliver exciting science, and thus attract young scientists who will lead future scientific ocean drilling investigations.

Because Earth's ocean is vast, a huge magnitude of unexplored space awaits your challenge. This 'inner space' invites you to understand Earth in four dimensions, in finer resolution, and to a wider extent. A dynamic system and supporting biosphere, Earth should genuinely arouse your curiosity in many ways. Confronting climate change and geohazards when the world population is rapidly growing, for example, immediately demands your greater understanding of the complex Earth system.

To meet such grand challenges, IODP will need to increase its interface with other scientific programs, each of which should consider IODP to be a vital partner. ICDP already demonstrates such a strategic partnership. And there are others who construct Earth in the cyber world or in labs, and who are developing observational networks, who are also natural partners.

As the scientific ocean drilling community gathers in Bremen to constructively look ahead constructively and build its future, I look forward to a successful INVEST meeting as a watershed event. Another step preparing for the future is the reorganization of IODP-MI into a single international office in Tokyo, starting in 2010.

Finally, I would like to emphasize that IODP-MI is about international access and mutual connection. We will strive further to gain your support for providing unbiased oversight and integration.

Continental Drilling Training Held in Sweden

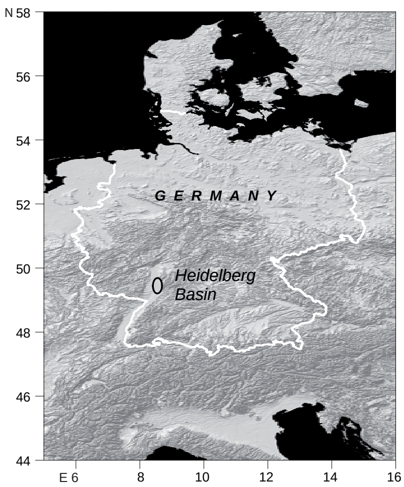
A specific ICDP Training Course on conti-nental scientific drilling was organized in cooperation with the Swedish Deep Drilling Program. From 18 to 22 May 2009, members of this working group, other interested scientists, and lecturers invited by the Operational Support Group met at Skokloster, Sweden to discuss key aspects of scientific drilling projects. In addition to basic modules of the ICDP training from planning to drilling, other topics that included data handling, long-term experiments, and specific projects currently under devel-opment in Sweden were addressed (http://www.sddp.se/projects). Furthermore, the capabilities and limits of truck-mounted drill rigs were presented and discussed, as the Swedish group has decided to develop and deploy such comparatively low-priced drilling tools with slimhole wireline coring capabilities to 2.5 km depth.

Integration of Deep Biosphere Research into Continental Drilling Campaigns

An ICDP workshop on the integration of deep biosphere research into continental drilling will be held at the German Research Centre for Geosciences–GFZ in Potsdam on 27–29 September 2009. This workshop will address scientific, technical, administrative, and logistical prerequi-sites for the integration of deep biosphere research into land-based scientific drilling. The development of adequate technical protocols to recover appropriate contamination-controlled sample material and the integration of a newly developed mobile microbial laboratory (GFZ BUGLab) will be issues of paramount importance. Furthermore, identification of upcoming ICDP drilling projects for deep biosphere research and new targets for dedicated conti-nental deep biosphere drilling projects in the future will be in the focus of the meeting. Researchers are invited from disciplines such as micro-biology, bio-geochemistry, geology, and geochemistry, along with engineers with experience and interest in deep biosphere research and drilling. Interested scientists and engineers are requested to contact Kai Mangelsdorf: k.mangelsdorf@gfz-potsdam.de or Jens Kallmeyer: jens.kallmeyer@geo.uni-potsdam.de.

Scientific Drilling of the Heidelberg Basin (Germany)

The Heidelberg Basin, part of the northern Upper Rhine Graben, hosts one of the thickest successions of Pliocene and Quaternary sediments in Central Europe. Since 2006 the basin has been explored by new core drill-ings of up to 500 m depth. The drilling activities are embedded in an interdisciplinary project that aims to better understand the geological evolution of the basin, the control by climate change and tectonics, and the correlation of the Alpine and North European glacial evolution.



First results are published by Gabriel et al. (*Quaternary Science Journal*, 57:3–4, 2008). Beyond a summary of the project, eight papers deal with aspects such as the geophysical pre-site surveys, concise descriptions of the core material, first results from geophysical downhole logging, and palynological analysis. The volume also includes a discussion of Pleistocene mollusks and exemplary studies on luminescence dating of fluvial sediments. The data indicate that Pleistocene deposits are more than 500 m thick and well-resolved in terms of the early Pleistocene pattern of cold and warm periods.

Lake El'gygytgyn Scientific Drilling Successfully Completed

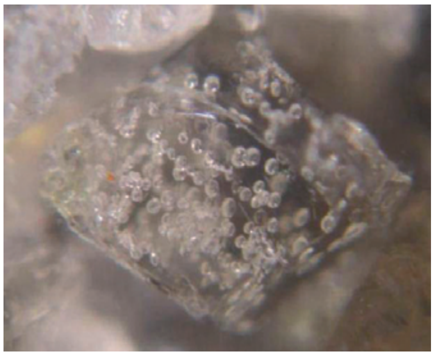
Between Octover 2008 and May 2009, an international team of scientists from Germany, the U. S., Russia, and Austria staged scientific drilling opera-tions at Lake El′gygytgyn, located in a 3.6-million-year-old impact crater in NE Russia. The project completed three holes in the center of the lake, reaching a depth of 517 m below lake floor, and one hole down to 141 m into permafrost deposits in the western lake catchment. The retrieved cores will provide new insights into the millennial-scale climate evolution of the Arctic, the formation of the meteorite crater, and the history of the permafrost. The successful completion of the project marks the end of years of challenging logistical planning (see previous issue of *Scientific Drilling*) and the develop-ment of international partnerships to share in the scientific goals.

Magma Drilled on Iceland!

An exciting event occurred on 24 June in the Iceland Deep Drilling Project (IDDP) at 2104 m depth. Suddenly the weight-on-bit declined while the rate of penetration and the torque shot up. After pulling up the drillstring a few meters, glassy rhyolitic cuttings followed by dark obsidian shards were circulated out, and it became clear that magma had been drilled.

The magma intrusion is presumably related to the nearby youngest eruptions in Northern Iceland (Krafla, 1975–1984). It may be a sill or dyke of unknown extension. However, due to the uncertainties it is now not feasible to continue drilling for supercritical fluids, the original goal of the IDDP. Nevertheless, the current surprise offers unique opportunities to study magma-fluid interaction at depth. Therefore, the well has been cased and cemented, and a slotted liner is set in the lowermost section. After surface valves are installed, tracer injection and flow tests will be performed to test connectivity to nearby wells and to produce superheated steam for research and eventually energy production from magma.

Depending on the results of these tests, future possibilities might include creating the world's highest-temperature Engineered Geothermal System (EGS). Details: http://iceland.icdp-online.org



Colorless rhyolitic glass shard (~1 mm across) with spherical vesicles (photo from ISOR daily report).

Book Review: *Drill Me a Painting* by Christine Laverne

Reviewed by Catherine Mevel

Atlantica, 2008.
ISBN: 978-2-7588-0169-6

Understanding how the ocean crust is formed and evolves through time has been a major goal of the successive ocean drilling programs DSDP, ODP, and now IODP. A number of cruises over more than thirty years have been dedicated to drill as deeply as possible into the ocean crust, with the ultimate aim of penetrating the Mohorovicic Discontinuity (MOHO). However, drilling through the basaltic flows of the upper crust and the sheeted dike complex into the gabbros has proved as invaluable as it has proven difficult. Only by 2005 was the lower gabbroic crust reached below *in situ* upper crustal lavas and dikes (Wilson et al., *Science*, 312(5776):1016–1020, doi:10.1126/science.1126090, 2006). As an expert in the alteration of ocean crust, Christine Laverne participated in seven of the cruises on the *Glomar Challenger* and the *JOIDES Resolution* that contributed getting this far. She shares her fourteen months of experience in a book *Drill Me a Painting*, beautifully illustrated with her own water colors.

The book is written in a lively, personal diary style telling about life on board. This narrative is interwoven with sections explaining the scientific goals placed in the general context of Earth dynamics, and providing information on the drill ships, the drilling techniques, and the measurements made on board. Christine elucidates how a drilling cruise is a team effort, with all the participants focusing on a single aim—to drill deep and explore the unknown. She conveys how discouragement and excitement can alternate in concert with the progress of the drilling. Readers can also sense how she herself evolves from an inexperienced young one to a recognized scientist in her field—a well of knowledge for the younger generations. She also clearly explains the scientific goals of drilling and how the results contribute to our current understanding of the ocean crust that cover two-thirds of our planet. The combination of watercolors and scientifically very sound explanations is particularly attractive.

Participation in ocean drilling is not only a scientific challenge. It is also a human adventure. This is the message that Christine Laverne conveys to the reader with her enthusiasm and painting skills. If you want to convince a relative, a friend, or a neighbor that ocean drilling is an exciting endeavor, offer him or her this book. For young people, especially, it could even attract them to a career in science.

Welcome on board!

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Schedules

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

	ESO Operations *	Platform	Dates	Port of Origin
1	325 - Great Barrier Reef Environmental Changes	MSP	Sep. 2009–Dec. 2009	TBD
	USIO Operations **	**Platform**	**Dates**	**Port of Origin**
2	324 - Shatsky Rise	*JOIDES Resolution*	04 Sep. 2009–04 Nov. 2009	Yokohama, Japan
3	317 - Canterbury Basin	*JOIDES Resolution*	04 Nov. 2009–04 Jan. 2010	Townsville, Australia
4	318 - Wilkes Land	*JOIDES Resolution*	04 Jan. 2009–09 Mar. 2010	Wellington, New Zealand
	CDEX Operations ***	**Platform**	**Dates**	**Port of Origin**
5	322 - NanTroSEIZE Stage 2: Subduction Input NanTroSEIZE—Riserless Observatory Casing	*Chikyu*	01 Sep. 2009–10 Oct. 2009	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–Aug. 2010	Anatolia, Turkey

Other ICDP operations were not yet confirmed before the editorial deadline.