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Scientific Drilling

Reports on Deep Earth Sampling and Monitoring

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Editorial Preface

Dear Reader:

This volume 14 of *Scientific Drilling* presents you with three new reports (pp. 4, 30, and 34) of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). This major project using the riser-drilling-capable drilling vessel *Chikyu* is now approaching the final and ambitious goal of drilling deep into a fault system that is known to repeatedly generate magnitude 8+ earthquakes. By the time this volume arrives at your desk, drilling of the final and deep riser hole will have begun. Actually, that was scheduled to have happened one year ago, but damage to *Chikyu* by the 11 March 2011 magnitude 9.0 earthquake and related tsunami caused a delay. Also, the Integrated Ocean Drilling Program (IODP) made it a priority to conduct a rapid response drilling into the fault that moved during the megaquake. The extremely demanding drilling in nearly 7000 meters of water within the Japan Trench was completed by *Chikyu* during July 2012 with successful logging, coring, and borehole observatory installation as much as 800 meters below seabed (p. 77). We hope to bring a report on this scientific and technological feat soon.

Lake drilling continues to be a highly important and successful component of the International Continental Scientific Drilling Program (ICDP). On page 18 we issue a report on the Lake Van, eastern Turkey drilling campaign. With its location and long history, it is well positioned to provide an important regional climate and environmental record including geohazards (earthquake history). A workshop report (p. 72) on the potential for lake deposit drilling near Mexico City is another example of how regionally important information regarding the environment (climate, water supply, and seismicity) can be amassed by scientific drilling and provide a context for the interpretation of much shorter historical records of environmental change.

As editors, we feel obliged to inform you that essential IODP funding of this journal is not yet secured beyond spring 2013. In order to establish viable funding for operations of the *JOIDES Resolution*, the U.S. National Science Foundation (NSF) will assess the merits of every component of the current program before deciding on what functions will roll over into the new International Ocean Discovery Program, which is planned to replace the current IODP by October 2013. The science plan for the new IODP is well established (www.iodp.org/science-plan-for-2013-2023) and, with Brazil recently joining the current IODP, is now supported by as many as 26 nations. What is also known at this point is that the U.S. commitment to the new IODP is secured for a one-year period to start in October 2013. This new program will not be centrally managed like the current IODP, but work more like a confederation of programs under the umbrella of a common science plan (p. 76). The feasibility of the new program structure and its funding model will need to prove successful before a final and long-term commitment of the *JOIDES Resolution* to the new IODP is made by the NSF.

So, please stay tuned for both important new science reports and program news in the spring 2013 issue of *Scientific Drilling*. It could be a collector's item–hopefully because of exciting good news on all fronts within scientific drilling.

Hans Christian Larsen
Editor-in-Chief

Ulrich Harms
Editor

Jamus Collier
Managing Editor

Front cover: Fine tephra layer that has been deformed in a microfold, indicating slumping, potentially induced by seismic shaking. (see page 26)
Left inset: Adding a clinometer data logger to a sensor carrier for the long-term borehole monitoring system (LTBMS) during Exp. 332. (see page 34)

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IODP is an international marine research drilling program dedicated to advancing scientific understanding of the Earth by monitoring and sampling subseafloor environments. Through multiple drilling platforms, IODP addresses its four principal challenges: Climate and Ocean Change, Biosphere Frontiers, Earth Connections, and Earth in Motion.

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

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IODP Expedition 333: Return to Nankai Trough Subduction Inputs Sites and Coring of Mass Transport Deposits

by Pierre Henry, Toshiya Kanamatsu, Kyaw Thu Moe, Michael Strasser, and the IODP Expedition 333 Scientific Party

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Abstract

Integrated Ocean Drilling Program (IODP) Expedition 333 returned to two sites drilled during IODP Expedition 322 on the ocean side of the Nankai Trough to pursue the characterization of the inputs to the Nankai subduction and seismogenic zone, as part of the Nankai Trough Seismogenic Experiment (NanTroSEIZE) multi-expedition project. Site C0011 is located at the seaward edge of the trench and Site C0012 on a basement high, Kashinozaki Knoll (Fig. 1). The main objectives of drilling again at these sites were to fill coring gaps in the upper part (<350 m) of the sedimentary sequence, to measure heat flow, and to core the oceanic basement to a greater depth on the Knoll. New results include the observation of a diagenetic boundary within the Shikoku Basin sediments that may be compared to one documented further west by ODP Legs 131, 190 and 196 but occurs here at a lower temperature. Borehole heat flow measurements confirm spatial variations in the Shikoku Basin that were indicated by short probe surveys. Heat flow variations between topographic highs and lows may be related to fluid convection within the basement. This expedition also included the objectives of the Nankai Trough Submarine LandSLIDE history (NanTroSLIDE) Ancillary Project Letter (APL) and cored at Site C0018 a pile of mass transport deposits on the footwall of the megasplay fault, a major out of sequence thrust that presumably slips coseismically during large subduction earthquakes. This brought new insight on the timing of these mass wasting events and on the deformation within the sliding slope sediments.

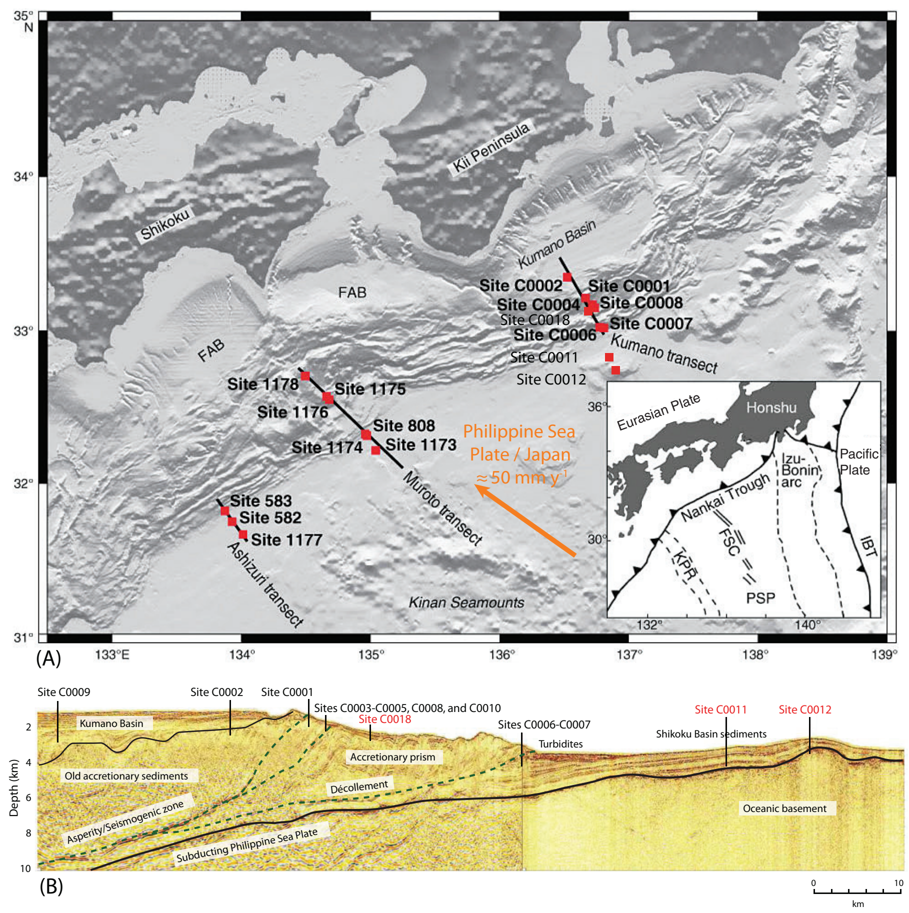

Figure 1. [A] Location map of Kumano, Muroto, and Ashizuri borehole transects across the Nankai Trough. FAB=Forearc Basin. [B] Spliced composite profile of a representative depth section from NanTroSEIZE 3D data volume (Moore et al., 2009) and Line 95 from IFREE mini-3D seismic survey (Park et al., 2008). Projected positions of Stage 1 and 2 drilling sites, including sites C0018, C0011, and C0012, are shown.

Introduction and Goals

To improve our understanding of earthquakes and tsunamis generated by subduction megathrusts, an ambitious project known as NanTroSEIZE was initiated along the subduction boundary of southwestern Japan in the Kumano transect area (Fig. 1). The overarching goal of NanTroSEIZE is to create a distributed observatory spanning the updip limit of seismogenic and tsunamigenic behavior (Tobin and Kinoshita, 2006a, 2006b). This multi-stage project is in the process of documenting several key components of the subduction margin, including the pre-subduction inputs of sediment and oceanic basement (Underwood et al., 2010), and the plate interface at shallow depths and at depths of 6–7 km where earthquakes occur (Tobin et al., 2009).

Exp. 333 addressed objectives at the NanTroSEIZE input sites seaward of the trench, Sites C0011 and C0012, as well as examined slope instability processes and their relationship with tectonic evolution proposed in the NanTroSLIDE APL. The characterization of the sedimentary column and ocean crust entering the subduction is essential because their evolution at increasing temperature and pressure presumably controls the transition to seismogenic behavior (Hyndman et al., 1997). Furthermore, the distribution of slip during earthquakes on faults affecting the shallow portion of subduction complexes determines locations of tsunami generation and their amplitude (Baba et al., 2006). The depth and frictional properties of the plate boundary fault and of splay faults connected to it may be controlled by the composition of incoming sediments, their diagenetic history, and the release and migration of fluids (Underwood, 2007). Heat flow is a vital measurement for the interpretation of diagenetic history, and it can also aid in identifying vigorous fluid circulation. Heat flow within the oceanic plate is also an important parameter for models calculating temperature along the subduction plate to the depth of the seismogenic zone (Hamamoto et al., 2011; Harris et al., 2011). This was not accurately constrained prior to this expedition.

The NanTroSLIDE APL arose from evidence gathered during earlier NanTroSEIZE drilling. IODP Expedition 316 found slumping near the fault scarp of the mega-splay, and 3D seismic reflection data revealed related mass transport deposits located further downslope (Strasser et al., 2011). Interpretation of 3D reflection seismic data and drilling results document a complex temporal and spatial evolution of the shallow mega-splay fault zone (MSFZ) and anticline structures in the underlying accretionary prism. This is characterized by a general decrease of thrusting motion with time since 2 Ma and alternating periods of high and low structural activity on individual structural segments (Strasser et al., 2009; Kimura et al., 2011). Site C0018 was drilled and cored to recover a Pleistocene-to-Holocene succession of stacked mass-transport deposits (MTDs) within a slope basin on the footwall of the megasplay thrust. Overall, drilling at Site C0018 aimed at (i) establishing a well-dated Quaternary submarine landslide history as it may relate to the tectonic evolution of the accretionary prism and (ii) reconstructing sliding and transport dynamics of submarine landslides as they may relate to the tsunamigenic potential of such event (Henry et al., 2010).

The specific set of questions addressed by Exp. 333 drilling is as follows.

- Is fluid circulation in basement and permeable sedimentary layers influencing heat flow and diagenesis at Sites C0011 and C0012?
- How does lithologic variation and diagenesis impact the physical properties of incoming sediments and guide fault development?
- Was magmatic activity heterogeneous in composition and age on the backarc basin basement high (Kashinosaki Knoll)?
- Is alteration of the upper oceanic basement heterogeneous, and how does such alteration influence geochemical and fluid budgets?
- What is the frequency of submarine landslides, what controls type, size, and magnitude of turbitides and MTDs, and how do related processes change through time?
- How do large MTDs relate to the timing of splay fault activity as inferred from NanTroSEIZE Stage 1 drilling?
- What are the dynamics of large submarine landslides, and can we infer their tsunamigenic potential?

Geologic Setting and Previous Work

The Nankai Trough is a convergent plate boundary where the Philippine Sea Plate underthrusts the southwestern Japan margin. At the Kumano transect across the Nankai Trough, the velocity between the Philippine Sea Plate and the forearc is 4.5–5.5 cm y^{-1} along an azimuth of $305^{\circ} \pm 3^{\circ}$ (Seno et al., 1993; Mazzotti et al., 2001; DeMets et al., 2010; Loveless and Meade, 2010) down an interface dipping 3°–7° (Kodaira et al., 2000b). The subducting lithosphere of the Shikoku Basin was formed by backarc spreading during a time period of 15–25 Ma (Chamot-Rooke et al., 1987; Okino et al., 1994). The three major seismic stratigraphic sequences identified in the northern Shikoku Basin are the lower and upper Shikoku Basin facies and local spill-over of Quaternary trench-wedge turbidites (Ike et al., 2008a). The lower part of the Shikoku Basin displays a complex geometry influenced by basement topography (Ike et al., 2008b). Basement highs are also imaged within the subduction zone (Kodaira et al., 2003; Dessa et al., 2004), where they influence margin structure (Lallemand et al., 1992; Le Pichon et al., 1996; Park et al., 1999; Mazzotti et al., 2002; Bangs et al., 2006; Moore et al., 2009) and seismicity (Kodaira et al., 2000a; Park et al., 2004). The NanTroSEIZE expeditions focused on the Kumano transect, while earlier Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) sites were drilled on the Muroto transect and the Ashizuri transects, respectively, in the central and western part of Shikoku Basin (Fig. 1; Moore et al., 2001). The combined data provide some information on input sediment variability at basin scale that may relate with margin structure. On the Kumano transect, swath bathymetry and multichannel seismic (MCS) data show a pronounced and continuous outer arc high extending >120 km along strike and marking the limit between the lower forearc slope and the forearc basin. The outer arc-high coincides with a splaying system of thrust faults that branch from a strong seismic reflector interpreted as a major out of sequence thrust, the megasplay fault (Park et al., 2002; Moore et al., 2007). Constraints on the slip history of faults are a major outcome of the previous NanTroSEIZE expeditions. The lower forearc slope of the Nankai Trough consists of thrust imbricates that were accreted to the margin over the last 2 Ma (Kinothis et al., 2009; Moore et al., 2009) but since 400,000–700,000 a, this wedge has been thrust over the trench sediments without accretion of new imbricates (Screaton et al., 2009). NanTroSEIZE expeditions also showed slip on the mega-splay is roughly synchronous with outer arc high uplift and subsequent Kumano forearc basin filling and tilting (Strasser et al., 2009; Gulick et al., 2010); however, in detail, long-term slip rates on individual splay thrust branches vary both in time and space (Kimura et al., 2011). The splay fault branch that was drilled slipped at rates ranging from 9 m kyr^{-1} to 2 m kyr^{-1} in the 2–1.5 Ma interval, but only at a very low rate (<100 m Ma^{-1}) over the last 1.3 Ma.

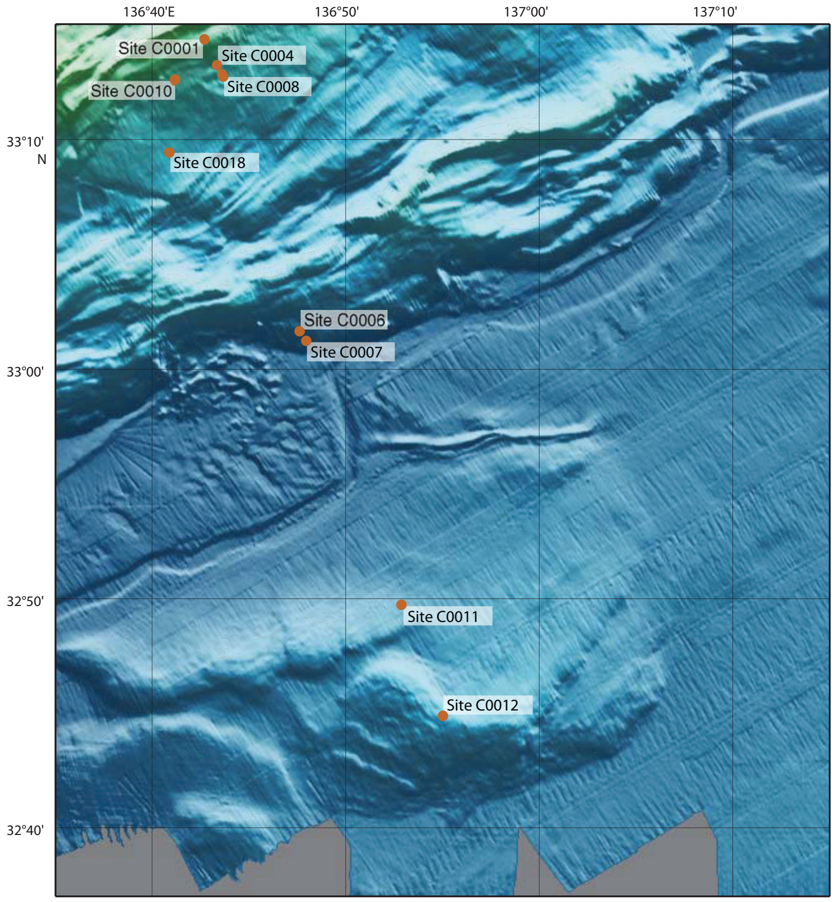

Figure 2. Detailed bathymetric map of Kashinosaki Knoll and Nankai Trough showing location of Sites C0011, C0012, and C0018.

Exp. 322 and 333 focused on two sites on the subducting Philippine Sea Plate. Site C0011 is located on the northwest flank of a prominent bathy-metric high (the Kashinosaki Knoll; Ike et al., 2008a), whereas Site C0012 is located near the crest of the knoll (Fig. 2). Portions of Sites C0011 and C0012 were drilled and cored during Exp. 322 in 2009, but important intervals were not recovered, and heat flow data were not obtained. The upper part of the sedimentary sections was either washed down or cored with rotary core barrel (RCB), which yielded cores of insufficient quality in the shallow unconsolidated sediments. The basement was reached at Site C0012 on top of the Kashinosaki Knoll and cored at 538–576 m below seafloor (mbsf). As a result, IODP Exp. 333 aimed to fill gaps in core data on the upper part of the sedimentary section, acquire much-needed measurements of borehole temperature to assess thermal history and the extent of *in situ* diagenesis, and drill and core to a deeper level in basement at Site C0012 to assess heterogeneity in composition and alteration.

Although the stratigraphic coverage was incomplete, the merger of lithofacies and age-depth models shows how correlative units change from an expanded section at Site C0011 to a condensed section at Site C0012 (Fig. 3). The composite section also captured a previously unrecognized interval of late Miocene volcaniclastic sandstone. An older (early–middle Miocene) turbidite sandstone/siltstone facies with mixed volcaniclastic-siliciclastic detrital provenance occurs in the lower Shikoku Basin facies; this unit may be broadly correlative with superficially similar Miocene turbidites on the western side of the basin (Fergusson, 2003; Underwood, 2007; Underwood et al., 2010). The age of basal sediment (reddish-brown pelagic claystone) at Site C0012 is older than 18.9 Ma.

Geochemical analyses of interstitial water on top of the basement high show clear evidence of upward diffusion of sulfate and other dissolved chemical species from the basement (Underwood et al., 2010). The depth of the sulfate reduction zone is also anomalously deep at Site C0012. Chlorinity values increase toward basement because of hydration reactions in the sediment and diffusional exchange with basement fluids (Underwood et al., 2010). In contrast to Site C0011, where chlorinity decreases with depth, the more saline fluids at Site C0012 are largely unchanged by the effects of focused flow and/or *in situ* dehydration reactions associated with rapid burial beneath the trench wedge and frontal accretionary prism.

Site C0018 is located ~3 km seaward from the splay-fault tip in a slope-basin that (1) represents the depocenter for downslope mass transport from the MSFZ, (2) is characterized by several MTDs identified in 3D seismic data (Strasser et al. 2011), and (3) includes an exceptionally large (as thick as 180 m) MTD. Drilling at Site C0018, which is located where the MTD bodies wedge out and where basal erosion is minimal, allowed for ground truthing and dating of the seismic-stratigraphic interpretation and sampling the MTDs across the most complete and thickest stratigraphic succession.

Site C0011

A total of 380 meters of sediment was drilled in Holes C0011C and C0011D (Fig. 4). Two lithologic units were identified with very good recovery rates (Expedition 333 Scientists, 2012a). Unit I corresponds to Shikoku Basin hemipelagic/pyroclastic facies, and Unit II corresponds to a volcanic turbidite facies that was originally designated middle Shikoku Basin facies (Underwood et al., 2010). In addition, two lithologic subunits were interpreted within Unit I, Subunit IA (younger) and Subunit IB. Cored lithologies include silty clay, clayey silt, clay, and mudstone interbedded with coarse to fine volcanic ash. The Subunit IA/IB boundary occurs at 251.52 mbsf and separates more indurated dark gray mud and mudstone from overlying sediments that are highly bioturbated. The sediments below the transition are also marked by the disappearance of volcanic ash layers with unaltered glass. Below 347.82 mbsf, which is the Unit I/II boundary, there is an abrupt shift into coarser-grained tuffaceous sandstone and heterolithic gravel and sand.

Four volcanic ash layers comprise provisional stratigraphic markers at Site C0011; they were correlated with dated ash layers on land (Fig. 4). These are Azuki (0.85 Ma), Pink (1.05 Ma), Habutaki (2.8–2.9 Ma) and Ohta (4.0 Ma) (Hayashida, 1996; Satoguchi et al., 2005; Nagahashi and Satoguchi, 2007). Shipboard paleomagnetic interpretations and nannofossil biostratigraphy, done post-cruise, agree well with these preliminary identifications. The shipboard paleomagnetic interpretation also has good continuity with Exp. 322 data and yields an age of 7.6 Ma for the transition between lithologic Units I and II, and the age of the Subunit IA/IB boundary is constrained to 5.32 Ma.

Structural features encountered in Hole C0011C and C0011D are rather sparse. Two sets of conjugate normal faults, striking NNE to SSW and NW to SE can be distinguished. The strikes of these conjugate sets are, respectively, parallel to the N25° maximum horizontal stress direction inferred from borehole breakouts at Site C0011 (Saito et al., 2010), and parallel to Nankai subduction convergence (300°–310°N; Mazzotti et al., 2001; Loveless and Meade, 2010). A NNE to SSW compression would be consistent with the local direction of compression inferred from kinematic modeling of the Zenisu-Izu fault system (20°N; Mazzotti et al., 2001). Furthermore, focal mechanisms of the 2004 earthquakes off the Kii Peninsula, which occurred within the oceanic plate north and northeast of Site C0011, indicate dominantly north–south compression (Ito et al., 2005). It is therefore likely that the state of stress at Site C0011 is influenced by intraplate compressive deformation within the Philippine Sea Plate.

Bulk density and resistivity values generally increase from the surface to 50 mbsf, reflecting normal consolidation of sediment. However, from ~50 mbsf to 80 mbsf density and resistivity decrease and then remain constant from 80 mbsf to 240 mbsf. Below 240 mbsf, density and resistivity increase abruptly across the transition between Subunits IA and IB and then continue along a normal consolidation trend. Two transitions were shown by logging-while-drilling (LWD) data at Site C0011 (Saito et al., 2010): one at 212 mbsf (downward decrease in gamma ray with a small associated decrease in resistivity) and one at 251.5 mbsf (downward increase in resistivity and gamma ray). The transition at 251.5 mbsf correlates with the abrupt porosity and resistivity change observed across the lithologic transition. However, the upper transition is not correlated with any remarkable observations on cores. During hydraulic piston coring system (HPCS) operations, downhole temperature was measured with the third-generation advanced piston corer temperature (APCT-3) tool at ~30-m intervals. We completed one measurement in Hole C0011C at 22.5 mbsf and eight measurements in Hole C0011D from 49 mbsf to 184 mbsf. Data show a nearly linear increase in temperature with depth (0.0913°C m^{-1}; Fig. 5), corre-

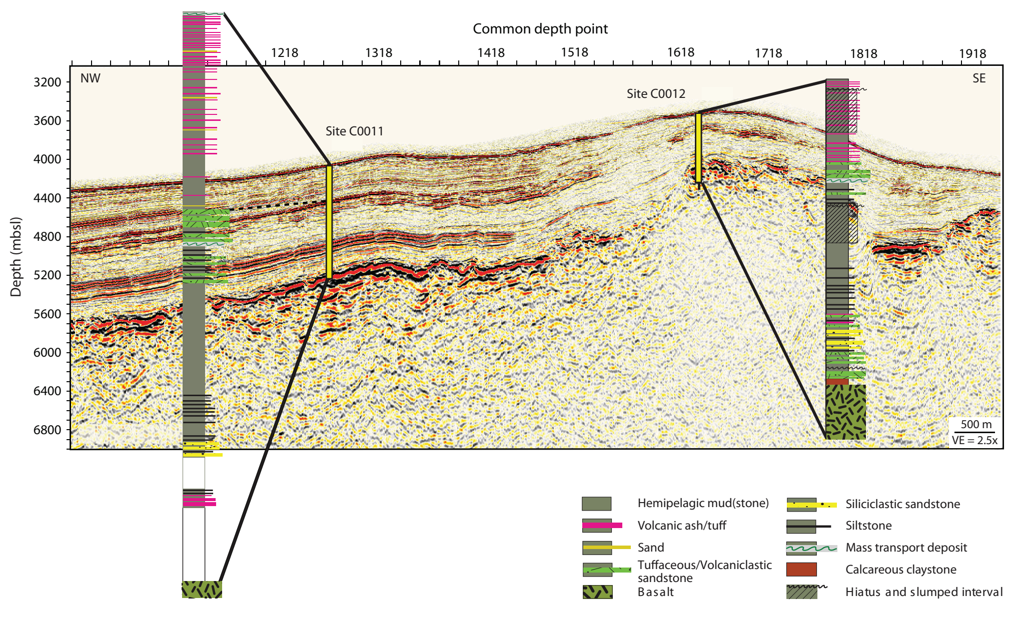

Figure 3. Lithologic columns on seismic background across Kashinosaki Knoll showing sites C0011 and C0012, using results from Expeditions 333 and 322 (Underwood et al., 2010). VE=vertical exaggeration.

sponding to a heat flow value of 89.5 mW m^{-2}. Temperature extrapolated at basement (~1050 m, from seismic profile), taking into account heat conductivity variations in the cored intervals, is ~80°C.

Interstitial water chemical composition trends are generally consistent with Exp. 322 results (Underwood et al., 2010). Chlorinity increases rapidly with depth in the upper ~25 m of Holes C0011C and C0011D, stays close to seawater value from 25 mbsf to 250 mbsf, and then gradually decreases. The chlorinity decrease, which continues to the deeper interstitial waters of Hole C0011B taken during Exp. 322 (Underwood et al., 2010), may reflect the updip migration of interstitial water freshened by the smectite-illite reaction at greater depths below the trench and prism toe. Sulfate concentration decreases rapidly in the upper 70 m of Hole C0011C, followed by a less dramatic decrease from 70 mbsf to 183 mbsf, which corresponds to the end of HPCS coring. The scatter of sulfate concentration below this level reflects seawater intrusion resulting from disturbance during coring. Yet sulfate probably remains present at low concentrations down to 280–300 m depth, which could explain why barium concentrations remain low and rise sharply below this level. Methane was the only hydrocarbon gas detected in holes C0011C and C0011D. It occurs only in low concentrations (2 ppmv) in the uppermost 260 m of the cored sequence and then rises to reach the highest values (~900 ppm) at the bottom of Hole C0011D. This indicates that, although sulfate consumption rate may be maximal at 70–80 m, the sulfate-methane transition zone occurs deeper, in the 250–300 m depth range.

Another remarkable feature is a sharp drop in silica concentration from ~800 ppm to ~200 ppm or less at the level of the transition from lithologic Subunit IA to IB. This drop correlates with a decrease in porosity from ~65 % to ~55 % observed over <10 m in moisture and density data, and with a concurrent resistivity increase in LWD (Saito et al., 2010) and core data. This behavior is similar to that observed at ODP Leg 190 Sites 1173 and 1177, where the base of the zone showing retarded compaction was ascribed to dissolution of opal-CT cement and precipitation of quartz (Spinelli et al., 2007). At the level of the tuffaceous sand-stones (350–370 mbsf), a second-ary silica concentration maximum is observed, which may be related to ash alteration.

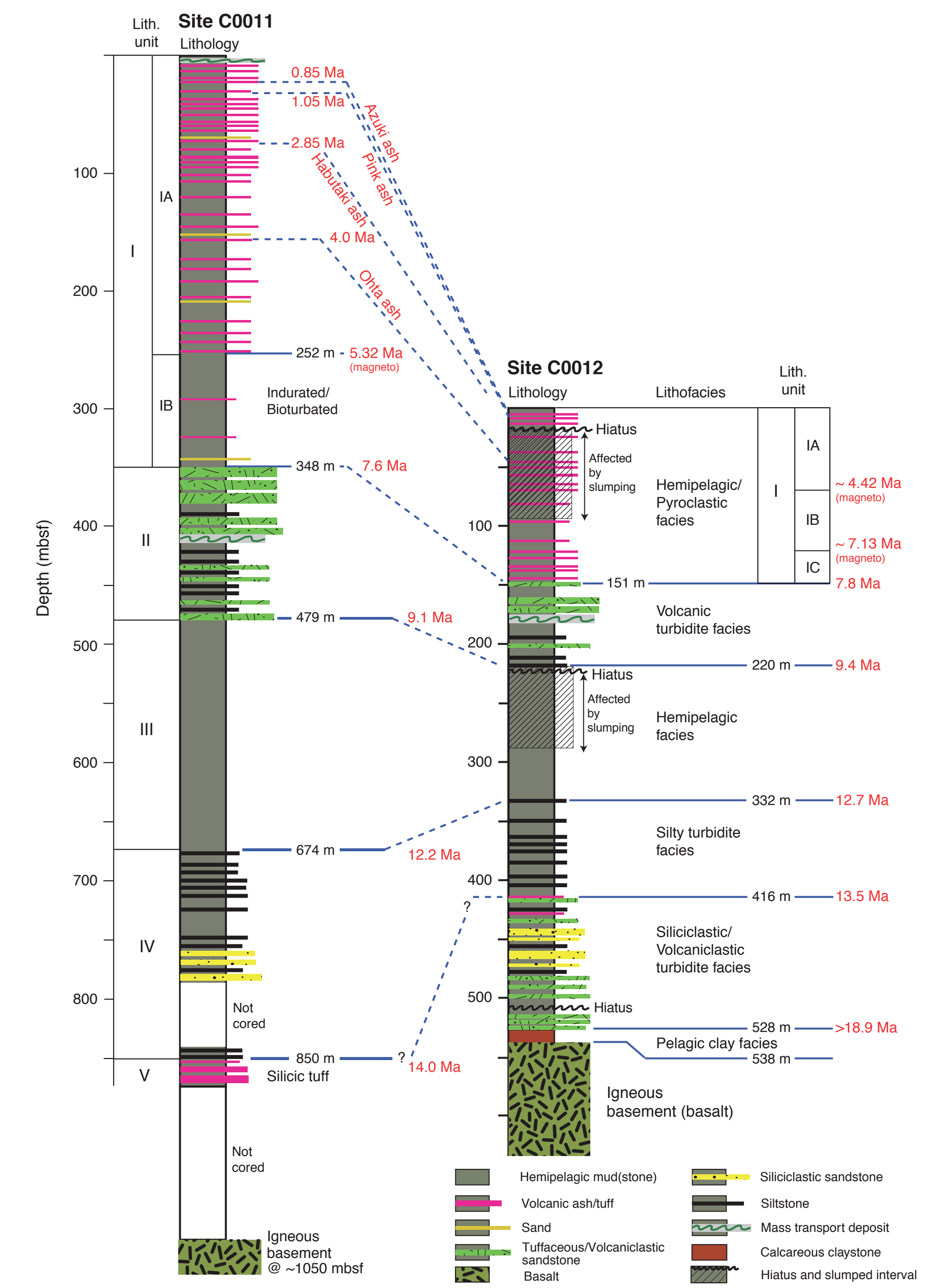

Figure 4. Stratigraphic correlation between Sites C0011 and C0012, based on composite lithology columns and age information from Expeditions 322 and 333. Unit boundary ages taken from integrated age-depth models.

Site C0012

In Holes C0012C and C0012D, 180 meters of lithologic Unit I (hemipelagic/pyroclastic facies) and the upper part of lithologic Unit II (volcanic turbidite facies) were drilled during Exp. 333 (Figs. 3, 4; Expedition 333 Scientists, 2012b). The remaining

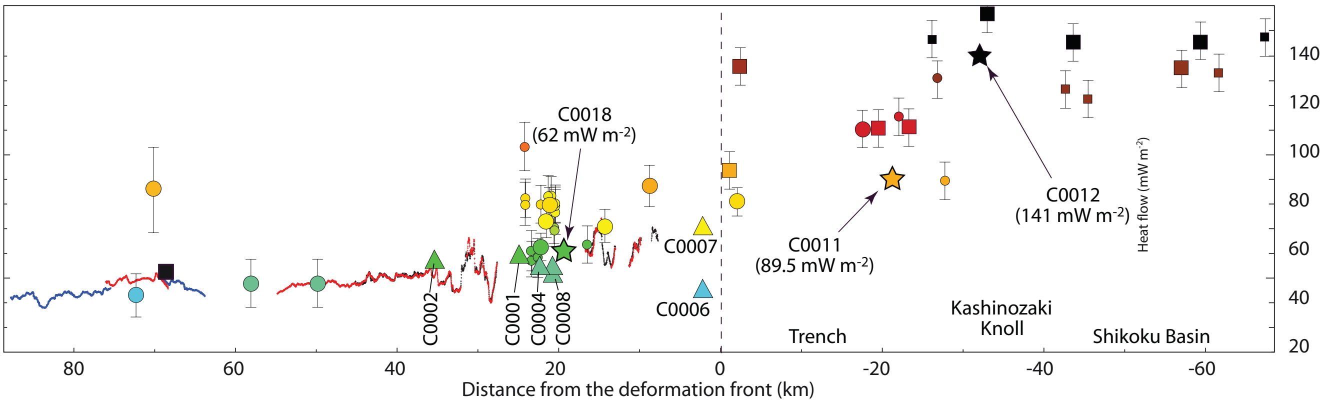

Figure 5. Heat-flow data collection in a 10-km-wide swath along the Kumano transect. Squares are heat flow probe measurements from Kinoshita et al. (2008), circles are long-term measurements from Hamamoto et al. (2011), triangles are borehole measurements from IODP Exp. 315 and 316, stars are from Exp. 333. The symbol sizes indicate data quality as defined by authors (big: good to excellent; small: poor to fair), the symbol color is a function of the heat flow value. Values derived from Bottom Simulator Reflectors (BSRs) along sections of multichannel seismic lines are plotted as lines.

holes (C0012E, C0012F, and C0012G) aimed at drilling red calcareous claystone and basalt at the contact between sediments in the Shikoku Basin and the igneous oceanic crust. Three lithologic subunits were interpreted in Unit I: Subunit IA (youngest), Subunit IB, and Subunit IC. The subunits are distinguished based on the presence, frequency of occurrence, and thickness of volcanic ash layers. The lithologies in Holes C0012C and C0012D include dark greenish gray clay and silty clay and silt interbedded with volcanic ash and minor occurrences of thin sand beds. A major decrease in the frequency of the occurrence of ash layers is recorded at ~71.5 mbsf, thereby defining the Subunit IA/IB boundary. Ash alteration was observed from 91.2 mbsf to the lower part of Subunit IB. At Site C0011, a comparable alteration front occurs at the top of Subunit IB. Ash layers are scarce to ~123.3 mbsf, which defines the base of Subunit IB. Another interval of dark greenish gray clay/silty clay-bearing ash layers corresponding to Subunit IC extends to 149.77 mbsf. This depth for the base of Unit I matches closely with the designation of 150.9 mbsf that was made during Exp. 322 (Underwood et al., 2010). Below 149.77 mbsf, Unit II comprises turbidite sands and sandstones with sharp and well-defined upper and lower boundaries. Commonly, beds have normal grading, but some comprise massive intervals with or without clay clasts. At the base of normally graded beds, pebble and sand clasts are composed of coarse ash and lapilli tuff. The lower part of Unit II comprises several layers of carbonate-cemented sandstones with calcite and barite veins. These beds are separated by mudstone very similar to that of Subunit IC.

Hole C0012E recovered two cores of greenish yellow mudstone intercalated with thin sandstone layers from 500 mbsf, corresponding to the base of lithologic Unit V (volcaniclastic-rich facies) defined during Exp. 322 (Underwood et al., 2010), and one core from 519 mbsf that recovered 6.8 m of reddish brown calcareous claystone with lighter green layers, overlying altered pillow basalts. The interface between the red calcareous claystone and the basaltic basement was also recovered in Holes C0012F and C0012G. The red calcareous claystone corresponds to Exp. 322 lithologic Unit VI (pelagic claystone; Underwood et al., 2010) and contains veins of calcite with traces of barite as well as several layers with accumulations of manganese oxide forming millimeter- to centimeter-sized lumps.

Hole C0012G cored pillows and massive phyric basalts from 525.69 mbsf to the base of the hole at 630.5 mbsf. Two units are defined in the basalt: Unit I is composed of phyric or highly phyric pillow basalt, and Unit II is composed of sheet flows with pillow basalt interlayers. As observed during Exp. 322, the basalt in Unit I is highly altered, and some voids remaining between basalt pillows are filled with analcime. Observations of thin sections showed that all olivine and most glass as well as a fraction of the plagioclases have been replaced by secondary phases—dominantly saponite, celadonite and zeolites—that are also present as vesicle fillings. In Unit II, the massive sheet flows are more crystalline and generally less altered. Basalt experienced localized alteration under iron oxidizing conditions with accumulation of iron hydroxides in veins and alteration halos. Celadonite and saponite are present in the rock mass and, locally, pyrite. This suggests two stages of alteration, under iron oxidizing and iron reducing conditions.

Bedding planes at Site C0012 display a large range of dipping angles from 3° to 70° but are organized in zones of low and high bedding dips. Bedding planes with low dips are characteristically observed between 0 mbsf and 14 mbsf and between 85 mbsf and 145 mbsf. High-dip angle beds are found between 14 mbsf and 85 mbsf where they consistently strike northeast–southwest and dip southeast, and between 145 mbsf and 180 mbsf, where the distribution of strikes and dips appears scattered. Chaotic structures (disrupted beds, folds, and injections of sand or mud) are observed at the bottom of the high-dip angle sections. Faults and shear zones mostly display normal displacement with high-dip angles, striking northwest–southeast, and dipping northeast or southwest, suggesting northeast–southwest extension. Considering the location of Site C0012 on a topographic high southwest of a steep arcuate slope evocative of a slide scar (Fig. 2), the interpretation proposed is that the high-dip angle sections have been affected by sliding events.

The cored portion of Units I and II has an estimated Holocene–Late Miocene age range (~0–8.3 Ma). Three ash beds were correlated to known tephra dated on land, based on visual observations of the shape of the glass shards and dominant associated minerals in smear slides. The Azuki volcanic ash bed, dated on land as 0.85 Ma (Hayashida et al., 1996), was identified at 5.7 mbsf. The Pink ash bed, dated on land as 1.05 Ma (Hayashida et al., 1996), correlates with a characteristic ash bed at 7.7 mbsf. A third major volcaniclastic event, the Ohta ash bed, dated on land as 4.0 Ma (Satoguchi et al., 2005), correlates with an ash bed at 44.95 mbsf. The unusually shallow depths of the presumed Azuki and Pink ash beds imply very slow average sedimentation rates over the last ~1 Ma. This interpretation is, however, consistent with the depth of the Brunhes-Matuyama reversal and of the Jaramillo Chron from natural magnetic remanence data. This interval of condensed sedimentation lies on an angular unconformity at ~14 mbsf, interpreted as the top of a slump. Paleomagnetic and biostratigraphic data suggest that this unconformity correlates with an age hiatus of ~2.0 m.y. (~1 Ma to ~3 Ma). Similar observations within the upper part of Unit III during Exp. 322 suggested that a slumping event associated with the remobilization of the uppermost sedimentary layers also occurred about 9.5 m.y. ago (Underwood et al., 2010). The transition from Subunit IA to IB is constrained at 4.42 Ma from magnetostratigraphy, and thus appears slightly younger at Site C0012 than at Site C0011. The change of the frequency of ash layer occurrence at the Subunit IB/IC boundary is constrained to 7.13 Ma from magnetostratigraphy. The age models at the depth of the transition from Unit I to Unit II are very consistent, and they provide an age of 7.8 Ma, slightly older than at Site C0011.

Porosity and resistivity measured on cores at Site C0012 present, as at Site C0011, an anomalous interval where these parameters remain constant with depth and do not follow a progressive compaction trend, whereas shear strength increases. This interval is found at a shallower depth range (~10 mbsf to 70 mbsf), and it displays a more progressive transition at its base from ~70 mbsf to 100 mbsf across the lithologic Subunit IA/IB boundary. Site C0012 porosity values from below 240 mbsf are generally lower than those from similar depths at Site C0011. A possible explanation for this observation is the removal of about 100 meters of overlying material by erosion or slope failure. This interpretation would be consistent with the observed time gap of ~2 m.y. found between 10 mbsf and 14 mbsf. Near the base of the sediments, calcareous claystones cored below 500 mbsf range in porosity from 0.28 to 0.46 and show P-wave velocities of ~2000 m s^{-1}. Within the basalt, measured porosity is extremely variable and ranging from 0.09 to 0.37, and measured P-wave velocities vary between 3000 m s^{-1} and 5000 m s^{-1}.

Thermal gradient values are evaluated from the APCT-3 measurements made at ten depths in Holes C0012C and C0012D together, and the mean thermal gradient value determined is 0.135 K m^{-1} (Fig. 5). The estimated heat flow value at this site is 141 mW m^{-2}, amounting to ~50% higher than the 89.5 mW m^{-2} determined for the adjacent Hole C0011C that was drilled during this expedition. Based on the determined heat flow value of 141 mW m^{-2}, as well as the thermal conductivity values from core measurements (Saito et al., 2010), temperature at the top of basement (at 526 mbsf) is estimated to be ~65°C, which is significantly lower than the estimated value of 80°C at ~1050 mbsf at Site C0011.

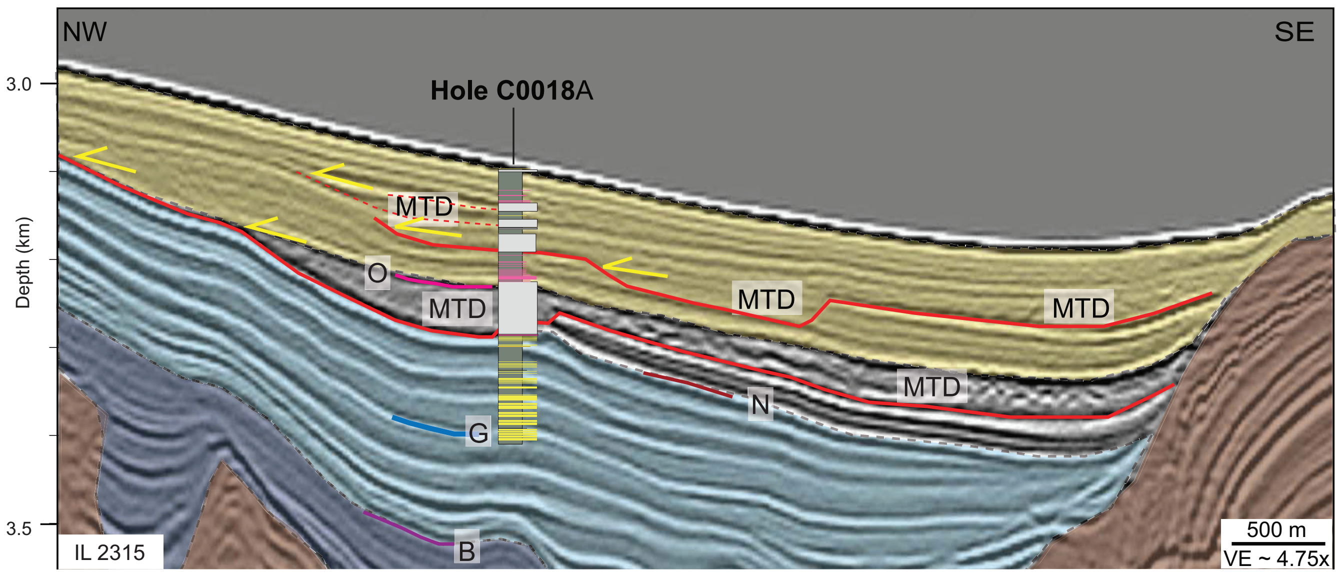

Figure 6. Lithology of Site C0018 on seismic profile. IL=in-line, VE=vertical exaggeration. Key seismic horizons are labeled B, G, N, and O MTD=mass transport deposit. Figure modified after Strasser et al. (2011).

As at Site C0011, results of interstitial water analysis are generally consistent between Exp. 333 and 322. Overall, the combined data sets reflect *in situ* alteration of volcanic ash in the sediment and basalt alteration in the upper igneous crust as well as exchange by diffusion (Underwood et al., 2010). The sulfate profile for Site C0012 indicates that sulfate reduction occurs at a deeper level than at the other sites drilled during this expedition. A minimum in sulfate concentration at ~300 mbsf was observed during Exp. 322, and this was interpreted as being driven locally by anaerobic methane oxidation (Underwood et al., 2010). In Holes C0012E and C0012A, sulfate increases in concentration in the interval below ~450 mbsf, which may indicate diffusional exchange with fluid in basaltic basement that sustain a higher sulfate concentration. A trend of increasing chlorinity, Ca, and Sr concentrations and decreasing Na in the lower part of the boreholes is also interpreted as a consequence of diffusion between the lowermost sediment and basement fluids. At a shallower level, samples from Hole C0012C document a silica concentration drop below the Subunit IA/IB boundary at ~70 m, where a decrease in porosity and an increase in resistivity are also observed. Alteration of volcanic glass shards also becomes more pronounced. As at Site C0011, this suggests a relationship between interstitial water composition, the presence or dissolution of opal-CT cement, and ash diagenesis.

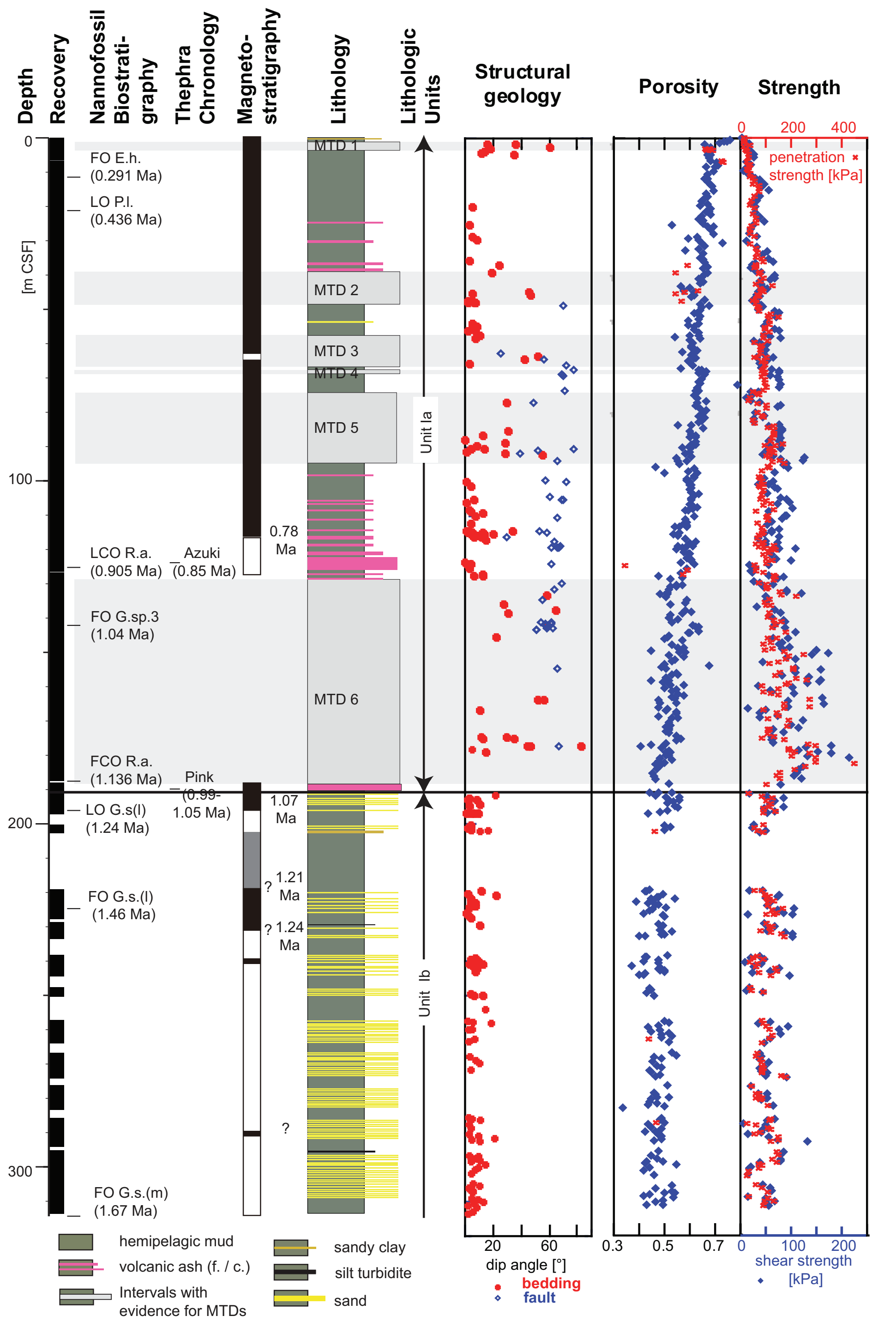

Figure 7. Summary diagram of IODP Expedition 333 Site C0018 shipboard results. Abbreviations for nannofossil data: F(C)O=first (consistent) occurrence, L(C)O=last (consistent) occurrence, E.h.=*Emiliania huxleyi*, P.l.=*Pseudoemiliania lacunosa*, R.a.=*Reticulofenestra asanoi*, G.sp.(l, m)=*Gephyrocapsa* species (large, medium).

In Holes C0012C and C0012D, methane and ethane were either below detection or present at only low concentrations. No heavier hydrocarbon gases (e.g., C3 and C4) were found. The only two samples that contained both methane and ethane were found at depths of ~501 mbsf and ~520 mbsf in Hole C0012E; they had C1/C2 ratios of <100, indicating a possible thermogenic origin of these hydrocarbon gases.

Site C0018

Sediments cored at Site C0018 (Fig. 6) are subdivided into two lithologic subunits (Expedition 333 Scientists, 2012c), which correlate with seismic Unit 1a and 1b of Kimura et al. (2011) and Strasser et al. (2011). Lithologic Subunit 1a is primarily composed of bioturbated hemipelagic mud intercalated with layers of varying coarse and fine volcanic ash. Six intervals with evidence of MTDs are observed within Subunit 1a (Fig. 7). MTDs at Site C0018 range in thickness from 0.5 m to 61 m and have a cumulative thickness of 98 m, thus accounting for half of the total thickness of Subunit 1a. MTD 6 correlates to the main MTD body identified in seismic data (Fig. 6; Strasser et al., 2011). The upper boundary/contact is well defined for MTDs 1, 2, and 6 and is marked by an MTD-overlying turbidite for two of them (MTDs 2 and 6). Shear zones in fine-grained sediments define the base of MTD 2, 3, and 5. Additionally, physical properties data (Fig. 7) show that MTD intervals display an increased compaction gradient (locally stronger porosity decrease with depth) compared with the linear porosity-depth trend which may be defined over the whole Subunit 1a, and slight reversals (porosity increasing with depth) are observed near the base of MTDs 2, 3, 5, and 6. A thick ash layer, which correlates to the onland tephra "Pink" dated 1.05 Ma (Hayashida et al., 1996), occurs at the base of MTD 6 and also defines the base of Subunit 1a at 190.6 mbsf. This age is supported by magnetostratigraphic constraints correlating the base of a short normal polarity interval immediately below the subunit boundary to the base of the Jaramillo subchron (1.07 Ma), and it is also consistent with the maximum age for this boundary estimated from calcareous nanno-fossils (<1.24 Ma). The Azuki ash layer (Hayashida et al., 1996) was identified above MTD 6, constraining its emplacement between 0.85 Ma and 1.05 Ma. Unit 1a thus spans from 0 Ma to ~1 Ma, and the average sedimentation rate is ~19 cm ka^{-1}. Minor normal faults with moderate to high dip angles (50°–80°) are developed in the lower part of Subunit 1a; they reflect vertical maximum principal stress likely in response to the sedimentation and burial processes within the slope basin. Progressive burial and consolidation are indicated by the general downward increase and decrease of undrained shear strength and porosity, respectively (Fig. 7).

Lithologic Subunit 1b comprises a sequence of sandy turbidites interbedded with silty clay. Sub-horizontally dipping 4–20-cm-thick sand layers typically show a sharp and erosional base and normal grading. Bed spacing is 20–30 cm in average, but muddy intervals up to 4 m thick without intercalated turbidites occasionally occur. Turbidite sands have mixed composition with quartz, plagioclase, and abundant lithic fragments of both metamorphic and volcanic origin, indicating a siliciclastic source. Averaged sedimentation rate within Unit 1b is ~40 cm ka^{-1}, higher than in Unit 1a. Porosity and undrained shear strength (measured in muddy intervals) are generally constant throughout Unit 1b, and they show values slightly higher and lower, respectively, than what would be expected from downward extrapolating the general trends from Unit 1a. The drop in shear strength below the subunit boundary may be related to the switch from HPCS at this depth to extended punch and extended shoe coring systems (EPCS, and ESCS, respectively), which cause more disturbance to the cores. If real, however, this observation may be interpreted to reflect a general state of slight underconsolidation, potentially resulting from the high sedimentation rates within this interval and the deposition of the thick MTD immediately above.

Key Results and Future Work

Shikoku Basin Stratigraphy and Diagenesis

Observations on HPCS, EPCS and ESCS cores complemented stratigraphic description in the upper part of the sedimentary columns drilled during Exp. 322. The new observations, however, did not bring major changes in the definition of lithologic units (Saito et al., 2010; Expedition 333 Scientists, 2011). The most remarkable new observations is the correlation between a sharp variation of physical properties (porosity and electrical resistivity; Fig. 8), which was already evident in the LWD data from Exp. 319, a drop in silica concentration, and a concurrent decrease of the abundance of ash layers and increase of their state of alteration. Glass shards from ash layers generally appear fresh above, but are variably altered below, with evidence for glass dissolution and replacement by clay minerals.

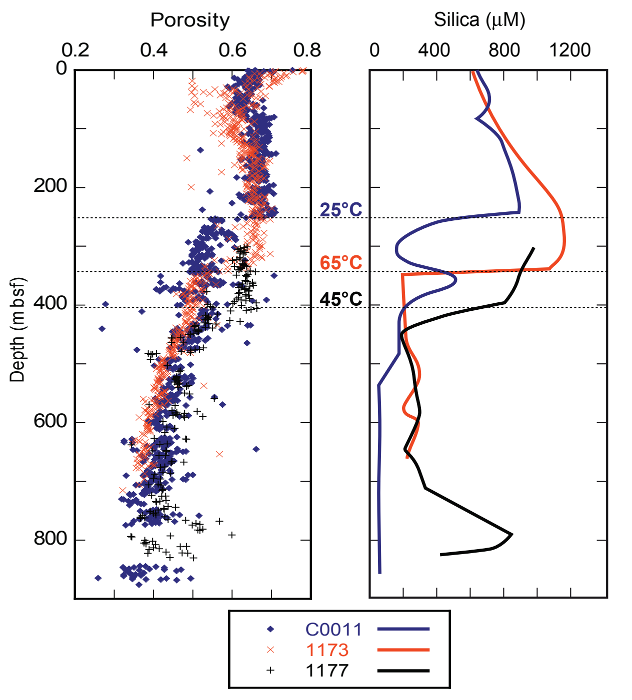

Figure 8. Porosity from sites C0011, 1173, and 1177 from moisture and density measurements, and silica concentration profiles in interstitial water. A concomitant drop of silica concentration and porosity is observed at all sites within the Shikoku Basin hemipelagites. This also correlates with a front of volcanic ash alteration. It was proposed that clay compaction is prevented by the precipitation of opal-CT cements at grain boundaries at the initial stages of diagenesis and that this metastable cement is then dissolved as temperature increases (Spinelli et al., 2007). The temperature estimated from borehole measurements at the depth of the transition is indicated. The diagenetic boundary is found at a different temperature at each site, which may help constraining the kinetics of the reactions.

The transition occurs within 10 m at 250 mbsf at Site C0011 but is found at a shallow level and is more progressive (50–80 m) at Site C0012. However, the sediment at this site has been affected by slumps, and this may preclude an accurate description of the transition. From an analogy with results obtained after Leg 190, it can be proposed that the process responsible for an anomalously high porosity of the sediment above this boundary is cementation by opal-CT and opal dissolution with precipitation of quartz below the boundary (Spinelli et al., 2007). However, the temperature of the reaction would be unusually low at Site C0011 (currently 25°C, as opposed to 65°C at Site 1173, see Fig. 8) and, assuming constant heat flow, it cannot be explained with the reaction kinetics used by Spinelli et al. (2007) because the kinetic time constants calculated at 25°C would be larger than the sediment age. The transition in physical properties is found at an even lower temperature (15°C) at Site C0012, but this may be in part explained by the removal of about 100 meters of sediment by the slump that occurred about 1 Ma ago. Furthermore, the primary silica source is dispersed volcanic glass rather than biogenic opal-A (White et al., 2011), and fresh glass is found again in volcaniclastic sands at a deeper level associated with high silica concentration in the interstitial water. It thus remains an open question whether the kinetics of the opal-A/opal-CT and opal-CT/quartz reactions can accurately model this transition. For instance, other kinetic models could be more appropriate for a volcanic ash silica source (Schacht et al., 2008). It is also possible that initial amorphous silica concentration immediately below the transition was too low to prevent compaction. Answering these questions will require postcruise work (e.g., amorphous silica content determination and modeling work). Chronostratigraphy based on paleomagnetism and biostratigraphy suggests that the age of the transition from opal-cemented hemipelagic mud with numerous ash layers to compacted hemipelagic mudstone with sparse ash layers at Site C0011 (5.25 Ma) is slightly younger at Site 1177 (4.5 Ma), the reference site for the Ashizuri transect. It is even younger at Site 1173 (2.5–3.0 Ma), the reference site for the Muroto transect, where higher heat flow and temperature can account for a more advanced silica diagenesis and result in an upward migration of the transition in the sedimentary column (Spinelli et al., 2007).

Overall, the temperature conditions at correlative stratigraphic levels do not vary by more than ~15°C between the two drill sites. Consequently, differences in fluid composition observed between the two sites (e.g., increasing versus decreasing chlorinity toward basement) cannot result solely from *in situ* reactions in the cored intervals. Temperature and heat flow determinations indicate that the temperature conditions in the uppermost basement at Site C0011 are within the temperature window for the onset of the smectite-illite reaction (~55°C–90°C), which has been proposed as the main cause of freshening at this site (Underwood et al., 2010). Although it is unlikely that the reaction has progressed to a significant extent in any of the cored sections, illitization should thus be expected in the lower part of Site C0011, and it should continue into the trench where the Shikoku Basin sediments are buried to greater depths. Unfortunately, coring during Exp. 322 was aborted almost 200 m above the top of basement at Site C0011.

Heat Flow and Convection

Exp. 333 provided the first borehole temperature measurements on the incoming plate of the Kumano transect, which constitute an essential constraint for subduction thermal models. Estimation of heat flow was conducted from linear regression of temperature as a function of thermal resistance. Heat flow thus obtained shows a good correspondence with heat flow probe and instrumented corer data (Fig. 5; Kinoshita et al., 2008; Hamamoto et al., 2011). The 90 mW m^{-2} heat flow at Site C0011 is in the lower range of heat flow probe values, while the 140 mW m^{-2} heat flow at Site C0012 is one of the highest. This result confirms the presence of a high heat flow anomaly on the Kashinozaki Knoll. However, constraints on the age of the oldest sediments at the base of C0012 are compatible with Kashinozaki Knoll having the same age (about 20 Ma) as the lithosphere in this part of the Shikoku Basin as indicated from magnetic anomalies (Chamot-Rooke et al., 1987; Okino et al., 1994). When compared with models, heat flow at Site C0011 appears slightly lower that the heat flow expected for a 20-Ma lithosphere (Kinoshita et al., 2008) but can be fit within uncertainties once the effect of sedimentation in the trench is taken into account (Marcaillou et al., 2012). Large-scale heat transfer from depth within the subduction zone to the trench by convection in the crust, as proposed for the Muroto transect to the west (Spinelli and Wang, 2008), appears unlikely on the Kumano transect because the heat flow remains moderate in the trench. However, 1- to 10-km scale heat flow variability could be caused at least in part by thermal convection. Because pore fluid geochemistry profiles from Exp. 322 and 333 do not provide evidence for fluid transfer between Site C0011 and Site C0012 along sedimentary layers, local convection in the basement appears the most likely explanation for the presence of a heat flow maximum in the summit area of Kashinozaki Knoll.

The Sediment-Basalt Interface and the Basalt

The basalt-sediment interface was cored three times during Exp. 333 with ESCS in Hole C0012E, and with RCB in Holes C0012F and C0012G. Although coring with ESCS was not the original choice, it was used to make the best of a short workable window between two periods of bad weather, and it provided good recovery of altered basalt including the inter-pillow hyaloclastites and analcime filled cavities. Multiple sampling of the red clay above the basement allowed recovery of larger amounts of pore fluid, which will be used for shore-based characterization of fluid isotopic composition (strontium, lithium, dissolved inorganic carbon). From an operational point of view, the use of a polycrystalline diamond compressed (PDC) bit turned out as inappropriate, as the bit was worn down to a point it was no longer functional even before basement coring started. As a consequence of weather-related and technical delays only two days were available for basement coring. One hundred meters were cored with patchy recovery. Pillows and massive flows of phyric basalt were recovered. As observed during Exp. 333, basalts were pervasively altered under iron reducing conditions, most of the glass, olivines, and part of the plagioclases being replaced by saponites and zeolites. Deeper penetration below the seafloor found occasional veins with accumulations of iron hydroxides. The sequence of alteration still needs to be determined. Knowledge of mineralogical composition of the altered basalt will allow quantifying fluid sources available from mineral reactions at the depth of the seismogenic zone, notably the saponite-chlorite reaction.

Mass Wasting and Mass Transport Deposits

The slope-basin stratigraphic succession drilled at Site C0018 documents ~1.5 million years of sedimentation by hemipelagic settling, turbidite, and mass-transport deposition in the footwall of the MGFZ. A lithological transition between a sandy turbidite sequence (below) and ash-bearing hemipelagites that contain MTDs (above) is dated to ~1 Ma (Fig. 7). Six MTDs of thickness 0.5–61 m were identified in the succession overlying this transition, but no positive evidence for MTDs within the turbidite sequence below has been found in the cores. During the same time period, a northward shift in the sediment depocenter is observed within the Kumano forearc basin following ~300 kyr of extensive landward tilting of the outer Kumano basin sediments. This has been interpreted to be related to an episode of motion along the megasplay that formed the modern fault geometry (Gulick et al., 2010). Hence, one possible explanation for the change in sediment delivery and routing pattern inferred from Site C0018 results is that the uplift of the outer arc high confined most of the turbidity currents to the Kumano Basin and thus progressively shut off sand input to the slope-basin seaward of the MSFZ (Strasser et al., 2012). Alternatively, the observed evolution could correspond to a local change of slope and depositional environment from a perched basin trapping sand transported by turbidity currents to a slope environment.

MTD 6 is correlative with this lithological transition and thus potentially may be related to the overall structural evolution of the MSFZ area and/or the change in sedimentation regime. However, all younger MTDs observed at Site C0018 postdate the main structural phase of slip on the shallow MGFZ and may be rather associated with shallow-seated slope failure processes within the post-1-Ma sedimentary cover overlying the MSFZ and anticline structure. The deformation style within these MTDs is heterogeneous; intervals of disturbed sediments are interbedded within intervals inferred to retain original, coherent bedding. In three occurrences the base of the MTD is defined by a shear zone within fine-grained sediments. These observations suggest that slumping and mass-transport are dominated by localized plastic deformation and that slumping only partly evolved into mud flows.

Mass movements are actively shaping the present-day seafloor, as evidenced by numerous surficial slump scars (Kimura et al., 2011; Strasser et al., 2012) and the occurrence of a shallowly buried, presumably Holocene, MTD at Site C0018 (Strasser et al., 2012). Further important findings are that the spacing between individual MTDs suggests submarine slope destabilization does not occur systematically during subduction earthquakes that have a recurrence rate on the order of 100–200 years (Ando, 1975). Hence, yet-to-be-investigated preconditioning factors may exert first-order control on destabilization processes and MTD formation over the last 1 Ma and in the future. These preconditioning factors will be the focus of upcoming studies integrating higher-resolution age constraints, more detailed sedimentological and structural investigations of MTDs, 3D-seismic interpretation and seismic attribute analysis, geotechnical laboratory analysis, as well as data and results from nearby IODP drill sites.

Site C0012 also appears strongly influenced by mass wasting processes. Slumps affecting sediment packages of 70–80 m thickness were identified during Exp. 322 and 333. Their top is marked by hiatuses (from ~1 Ma to 3 Ma and around ~9.5 Ma, respectively), and an even longer hiatus is evident along an unconformity within Unit V near the base of the sedimentary section. Repetition of mass wasting events is very understandable considering the location of Site C0012 on a topographic high immediately above the edge of a major slide scar observed in the bathymetry and seismic data.

Summary and Conclusions

Borehole heat flow data from Exp. 333 constrain heat flow in the trench and provide a reliable seaward boundary condition for modeling of temperature along the subduction interface (Marcaillou et al., 2012). A sharp contrast in physical properties in the Shikoku Basin hemipelagites is interpreted as a diagenetic boundary, present throughout the basin, and related to the diagenesis of high-silica volcanic ash. This diagenetic boundary is diachronous, and the geometry of turbidite bodies in the lower part of the Shikoku Basin displays considerable variability (Underwood, 2007; Underwood et al., 2010). Nevertheless, an interval of sedimentation deprived of fresh volcanic ash and turbidites is found on the three transects investigated by IODP drilling in the Nankai area. This broadly corresponds to the 4–7 Ma time interval. This interval appears as a favorable interval for the localization of the decolletment of the accretionary wedge but also for the localization of basal shear of slumps at Sites C0011 and C0012. Sampling of cores for geotechnical and mechanical tests will address this problem.

A sequence of cored mass transport deposits remobilizing slope sediments in the shallow MGFZ area documents ~1 million years of submarine landslides in this tectonically active setting (Strasser et al., 2012). Although earthquakes are an obvious potential triggering factor, these mass wasting events appear much less frequent than large earthquakes along this subduction segment. Thus, preconditioning factors such as sedimentation, tectonic loading, and fluid flow must exert key control on slope destabilization, and they are the focus of future investigations. Evidence from Sites C0011 and C0012 shows that large mass wasting events also occurred on topography on the downgoing plate and could explain some of the hiatuses observed within accreted sediment packages.

The basement appears altered by low temperature interaction with pore fluid of seawater origin over at least 100 m. Fluid convection is likely to occur in the fractured basement, but it constitutes a hydrological system largely distinct from the sediment, which comprises clay-dominated intervals that form barriers to flow, at least in the vertical direction. Release of water from mineral reactions will occur both in the sediment and in the basement, as they are buried below the sedimentations in the trench and underthrust beneath the margin. Modeling this evolution will likely be an important objective of post-cruise work.

The IODP Expedition 333 Scientific Party

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500,000 Years of Environmental History in Eastern Anatolia: The PALEOVAN Drilling Project

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Abstract

International Continental Scientific Drilling Program (ICDP) drilled a complete succession of the lacustrine sediment sequence deposited during the last ~500,000 years in Lake Van, Eastern Anatolia (Turkey). Based on a detailed seismic site survey, two sites at a water depth of up to 360 m were drilled in summer 2010, and cores were retrieved from sub-lake-floor depths of 140 m (Northern Basin) and 220 m (Ahlat Ridge). To obtain a complete sedimentary section, the two sites were multiple-cored in order to investigate the paleoclimate history of a sensitive semi-arid region between the Black, Caspian, and Mediterranean seas. Further scientific goals of the PALEOVAN project are the reconstruction of earthquake activity, as well as the temporal, spatial, and compositional evolution of volcanism as reflected in the deposition of tephra layers. The sediments host organic matter from different sources and hence composition, which will be unravelled using biomarkers. Pathways for migration of continental and mantle-derived noble gases will be analyzed in pore waters. Preliminary $^{40}Ar/^{39}Ar$ single crystal dating of tephra layers and pollen analyses suggest that the Ahlat Ridge record encompasses more than half a million years of paleoclimate and volcanic/geodynamic history, providing the longest continental record in the entire Near East to date.

Background and Motivation

The controversial discussion of present and future global warming has demonstrated that it is crucial to increase our knowledge of past climate change to better understand the pattern and dynamics of the global climate system. In continental regions this information can be obtained from lacustrine sediments, where biotic and abiotic parameters provide proxy climate data. In addition, lake sediments constitute unique paleoenvironmental archives storing also information of geologic disasters such as earthquakes or volcanic eruptions. Lake Van in Turkey is an excellent paleoclimate and paleoenvironmental archive, as site survey data indicated that it contains a long continental sedimentary record covering several glacial-interglacial cycles consisting partly of annually-laminated sediments.

Favorable geological conditions in the eastern Mediterranean and the Near East, such as relatively undisturbed accumulation of continuous Quaternary sediments, are rare. Successions such as the pollen records from Tenagi Phillipon and Joannina in Greece (Tzedakis et al., 2001) or from Lake Urmia in NW Iran (Djamali et al., 2008) document climatic changes over the continent on centennial to orbital time scales. These sequences enabled tentative comparisons with the marine isotopic record based on tuning to astronomical parameters, and showed that many stages and substages of the marine isotopic sequence are reflected in continental records. However, the timing of the transitions between them may not be precisely synchronous in the marine and continental realms. Lake Van holds a key position within

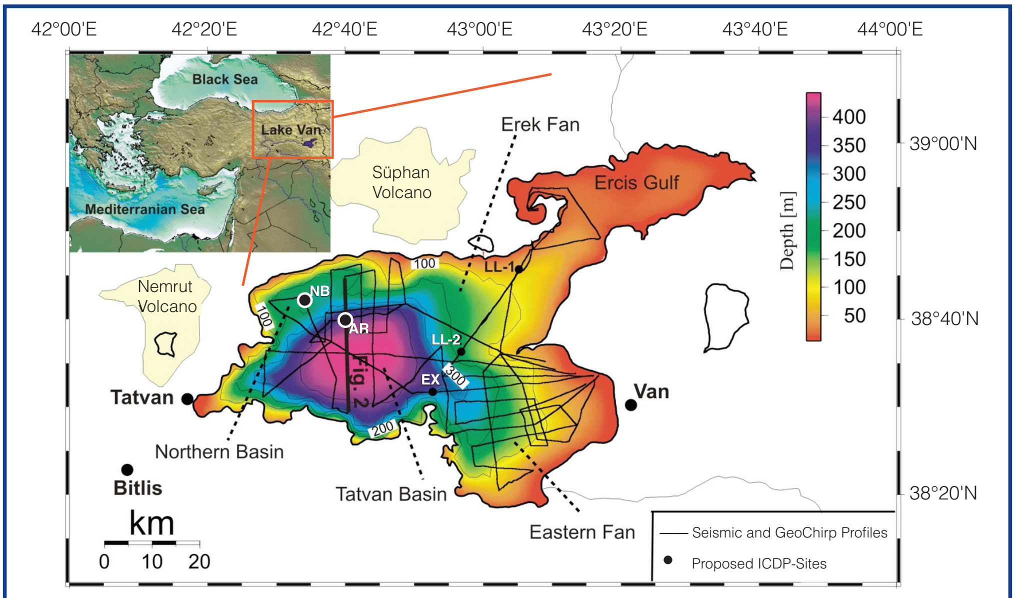

Figure 1. Bathymetric map of Lake Van with location of available seismic profiles and originally proposed drill sites. Ahlat Ridge (AR) and Northern Basin (NB) were finally drilled.

a sensitive climate region between the Mediterranean, Black, Caspian, and Arabian seas allowing for studying Quaternary climate evolution in the Near East during the last ~500 kyr (Litt et al., 2009, 2011). The Lake Van record drilled in 2010 is longer than those of Lake Urmia and Lake Joannina. In addition, the Van record will have a higher resolution and will be better dated than all of these previous records.

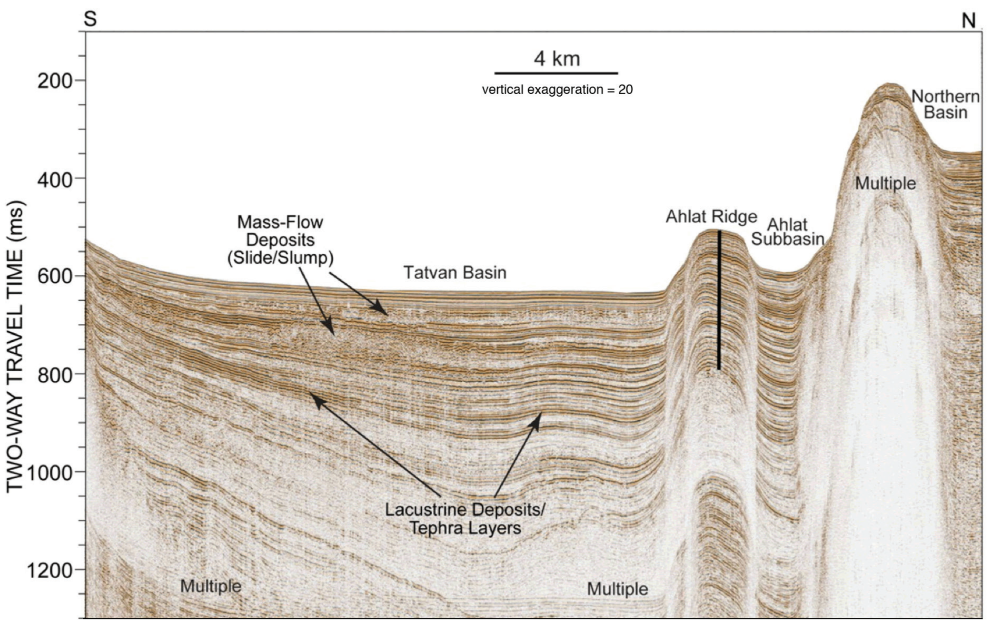

Figure 2. Seismic profile crossing the Tatvan Basin, Ahlat Ridge, and Northern Basin. Ahlat Ridge was selected as key site for the ICDP campaign in order to drill recover a complete sedimentary section for paleoclimatic investigations all the way to basement. See Fig. 1 for location of profile.

Lake Van, situated on a high plateau in eastern Anatolia, extends ~130 km WSW-ENE (Fig. 1). The lake level at present is 1647 m above sea level (a.s.l.) As the fourth largest (by volume) terminal lake in the world and largest soda lake (607 km^3, maximum depth 460 m; Kadioglu et al., 1997), it is situated in a region where the Afro/Arabian Plate from the south meets the Eurasian Plate from the north and east. Lake Van fills a tectonic depression within an active fault system that is the cause of regional volcanism and seismic as well as hydrothermal activity (Degens and Kurtman, 1978; Keskin, 2003; Kipfer et al., 1994; Litt et al., 2009; Şengör et al., 2003). Evaporation processes, hydrothermal activity, and chemical weathering of volcanic rocks, together with a supply of alkaline tephra into the lake basin, are responsible for the extreme alkalinity of the lake water (pH 9.8, salinity 21.4‰). Two active volcanoes Nemrut (3050 m a.s.l.) and Süphan (4058 m a.s.l.) rise in the immediate vicinity of the lake (Fig. 1).

The lake's position in a semiarid area at the junction of the atmospheric southwestern jet stream and northern branch of the Subtropical High makes it climatically sensitive. The jet stream steers the cyclone tracks that are responsible for supplying moisture from Mediterranean air masses during winter. The location of the Subtropical High controls the southward extension of the dry continental air masses of northeastern Europe and Asia (Litt et al., 2009).

Terminal and saline, Lake Van reacts very sensitively to lake-level changes caused by any alterations in the hydrological regime in response to climate change. Subaerial paleoshorelines and sedimentological evidence show that the lake level fluctuated up to several hundred meters in the past (Landmann et al., 1996; Lemcke and Sturm, 1997). No erosional unconformity could be detected in the younger lacustrine sections on seismic data below 250 m water depth, limiting the maximum lake-level drop to that depth. These

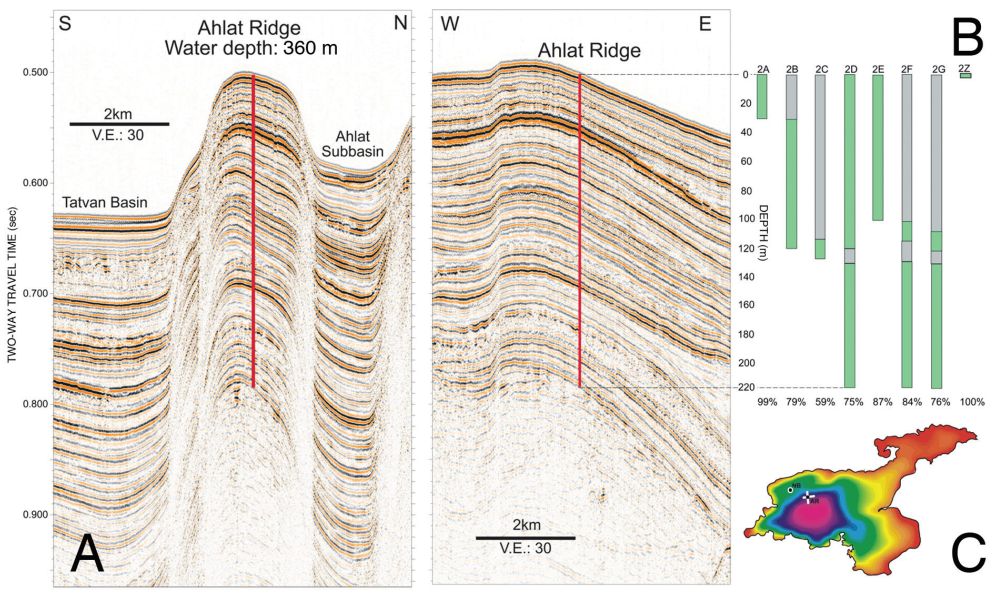

Figure 3. [A] Seismic lines crossing the Ahlat Ridge site. [B] Green bars show the cored sections of the multiple holes 2A–2G; 2Z is the gravity short core. The numbers give the recovery of the individual holes. [C] Location of drill site within lake bathymetry (white).

lake-level changes are sensitively recorded in the lithological and geochemical composition of Lake Van sediments and in the pore-water geochemistry. In particular, the oxygen isotopic composition of the bulk carbonate, consisting of almost pure authigenic aragonite, provides a powerful proxy to track the lake-level fluctuations during the last 15–20 kyr (Lemcke and Sturm, 1997; Litt et al., 2009; Wick et al., 2003). Such a dominance of authigenic carbonate precipitation is also expected from the older sedimentary succession, so that isotope geochemical studies will be the tool of choice for reconstructing the past precipitation/evaporation ratio.

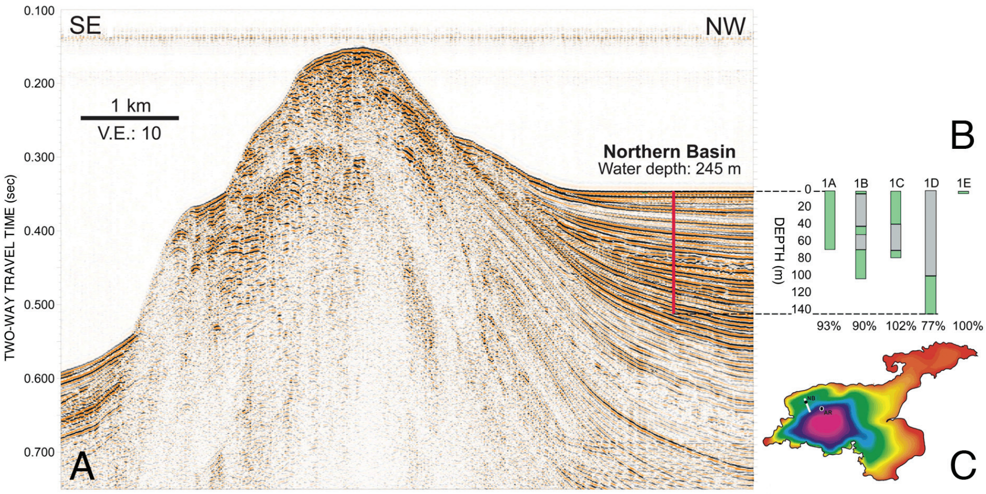

Figure 4. [A] Seismic line crossing the Northern Basin site. [B] Green areas show the cored sections of the multiple holes 1A–1D; 1E is the gravity short core. The numbers give the recovery of the individual holes (values >100 % caused by gas expansion). [C] Location of drill site within lake bathymetry (white).

The Lake Van area is strongly affected by earthquakes, a catastrophical natural hazard in the region. An earthquake with a magnitude of 7.2 just north of the city of Van on 23 October 2011 caused more than 600 casualties and major infrastructural damage in the region. In order to investigate recurrence rates of such events and to support seismic hazard studies, long paleoseismic records are needed that document the succession of strong earthquakes and past seismic activities for this tectonically active area. Short sediment cores obtained in 2004 also show strong evidence of earthquake-triggered microfaults, which can be interpreted as seismites (Litt et al., 2009). Consequently, one goal of the PALEOVAN drilling project (http:www.paleovan.info/) was to establish an extended paleoseismic event catalogue on the basis of the deep drill cores.

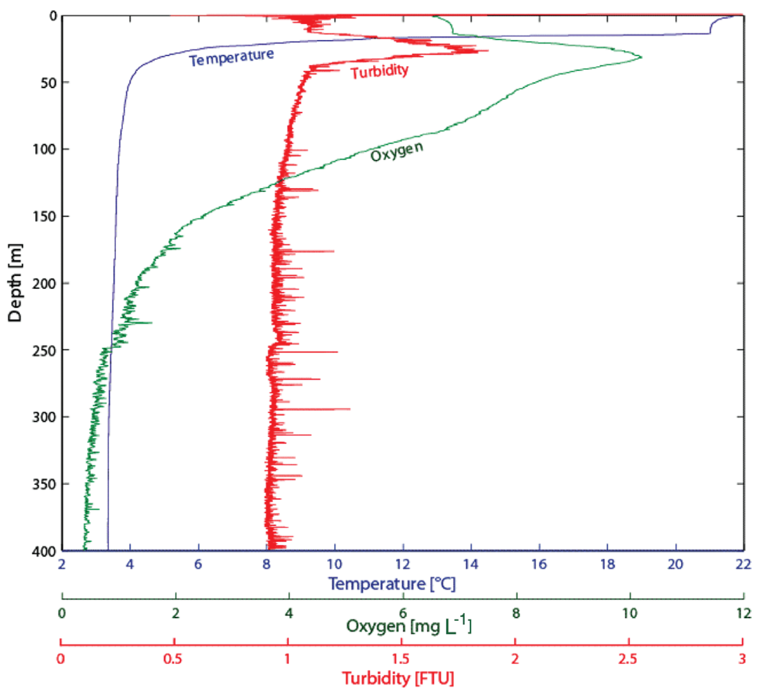

Figure 5. Temperature, turbidity (Formazin Turbidity Units), and oxygen profiles acquired with a CTD probe at the Tatvan Basin mooring site on 28 August 2009 (from Stockhecke et al., 2012). Note that oxygen content is not calibrated, in particular at lower concentrations.

A major benefit of choosing Lake Van as a drill site was the likelihood of recovering several hundred tephra layers from the active Nemrut and Süphan volcanoes towering Lake Van (Fig. 1), which would provide a tephrostratigraphic framework and allow single-crystal $^{40}Ar/^{39}Ar$ dating. Pre-site work has documented several tens of fallout and flow deposits originating mainly from the alkaline Nemrut volcano, including some eruptions of large magnitude (Sumita et al., 2012). Nemrut volcano has been active in historical times, and future eruptions are likely; therefore, knowledge of its past activity is critical to evaluate the current volcanic hazard.

Due to its unique geological and tectonic settings, Lake Van accumulates helium from a depleted Earth mantle source (Kipfer et al., 1994). On regional scales, such a release and transport of He from the solid Earth into the atmosphere is poorly understood. As lakes cover larger areas, they become prime targets to analyze the transport and release mechanism of terrestrial He from the solid Earth. The long profile from Lake Van will allow determination of the *in situ* terrestrial He gradient as a function of depth within a sediment column of several hundred meters. These data will provide the first insights into the transport processes of crustal and mantle He through the uppermost layers of the crust and improve the cur-

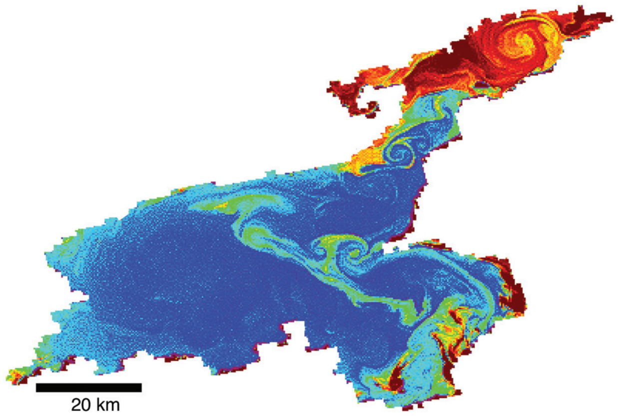

Figure 6. Satellite image (550 nm at-sensor radiance) of Lake Van taken on 20 September 2006. Note the wind-driven surface eddies redistributing suspended surface-water particles mostly consisting of authigenic carbonate ("whitings").

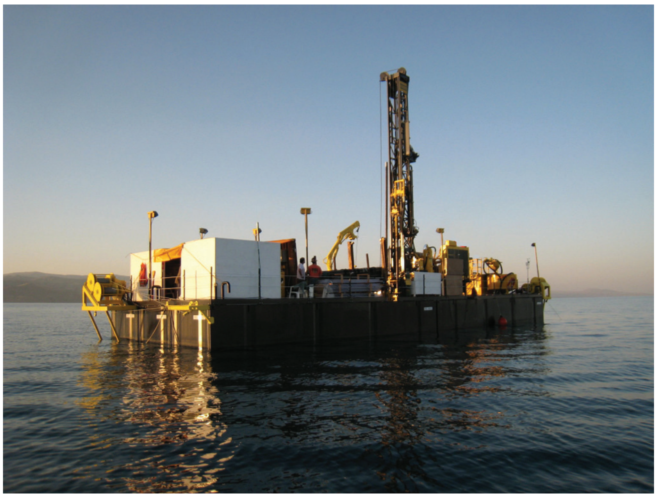

Figure 7. The new large Deep Lake Drilling System (DLDS) operated by DOSECC with the new top-head-drive rotary rig.

rent understanding of terrestrial fluid transport within the continental crust.

Site Surveys

Reflection Seismic Surveys

A seismic site survey at Lake Van was carried out in 2004 (Litt et al., 2009). In total we collected fifty profiles with a length of ~850 km by means of a high-resolution multi-channel and GeoChirp system (Fig. 1). Three physiographic provinces can be identified based on the seismic data: a lacustrine shelf, a lacustrine slope, and a deep, relatively flat lake basin province (Figs. 1, 2).

The lake has two prominent basins (Tatvan and Northern Basins; Fig. 1), separated by basement rises or ridges. The seismic units in the Tatvan and Northern Basins are largely characterized by an alternating succession of well-stratified and chaotic reflections (Fig. 2). The chaotic seismic facies are interpreted as slump and slide deposits, which were triggered by quick lake-level fluctuations and/or earthquakes. The moderate-to-high-amplitude, well-stratified facies seen in the deep parts of the basins are interpreted as background lacustrine deposits and tephra layers.

The most prominent features of the lacustrine shelf and slope are prograding deltaic sequences, numerous unconformities, submerged channels, as well as closely spaced U- and/or V-shaped depressions (Litt et al., 2009), reflecting the variable lake-level history of Lake Van. Seven clinoform units that are found in the Eastern Fan (Fig. 1) possibly represent relict deltas formed during periods of stationary or slightly rising lake levels. Various volcanic intrusions and extrusions have been identified in the southern part of the lake. Their occurrence closely follows the trend of the northern thrust fault, suggesting a close relationship between the thrust faulting and the volcanic activity.

Based on the high-resolution seismic data collected in 2004, five primary sites were selected (Fig. 1). The Ahlat Ridge site (AR) is the deepest (water depth ~360 m) and most important one (Figs. 1, 3), drilled in order to recover a complete sedimentary section for paleoclimatic investigations. The AR site is located on a sedimentary ridge preventing accumulation of mass-transport deposits, which are widespread in the Tatvan Basin (Fig. 2). On the other hand, the detailed analysis of the seismic data shows that a continuous sedimentary succession without major hiatuses can be drilled at this location down to at least 220 m subsurface depth (Fig. 3).The Northern Basin site (NB) is close to the northern shore of Lake Van (Figs. 1, 2, 4). The proximity to the Süphan and Nemrud volcanoes allows for studying major volcanic eruptions and associated volcanogenic hazards.

Only these two sites were drilled in 2010. Three additional sites were proposed, but their drilling was canceled due to financial limitations. Two sites in different water depths at the Erek Fan (LL-1 and LL-2) were planned to investigate lake-level fluctuations and the evolution of Lake Van. Finally, one site (EX) was proposed to examine the origin of widespread extrusions and intrusions, which are important for the tec-tonic setting of the lake.

Monitoring Modern Limnology

Next to the geophysical site surveys, several limnologic and short-coring campaigns as well as remote-sensing data analysis were undertaken. Numerous conductivity, temperature, and depth (CTD) profiles documented the stratification and mixing behavior of the lake (Fig. 5). The turbidity profile from a late summer profile (Fig. 5) shows a thick layer of suspended particles in the metalimnion at 15–40 m depth accompanied by an oxygen maximum, both indicative of algal blooms and carbonate precipitation. Below, oxygen concentration decreased with depth, and at ~250 m water depth, a drop in oxygen concentration combined with a rise in turbidity can be interpreted as a transition from oxic to anoxic water conditions (Kaden et al., 2010). Satellite data from the different seasons image the wind-driven surface currents of the lake, distributing particles in several eddies (Fig. 6; Stockhecke et al., 2012). The reflectance of the water mostly indicates differences in concentrations of suspended particles from ongoing authigenic carbonate precipitation ("whitings"). The annual particle cycle has been further documented in three years of sediment-trap data. It was shown that carbonate precipitation usually occurs in spring and fall, when runoff (snowmelt and precipitation) supplies Ca ions, which favor carbonate precipitation (Stockhecke et al., 2012). In winter, the fine-grained suspended material (organic and clay particles) settle and form the dark laminae of the varved layers, so that Lake Van sediments provide an annually layered sediment archive (Landmann et al., 1996; Litt et al., 2009, 2011; Wick et al., 2003). Sediment-trap data also documented the annual cycles in biomarkers as well as in terrestrial supply (Huguet et al., 2011, 2012).

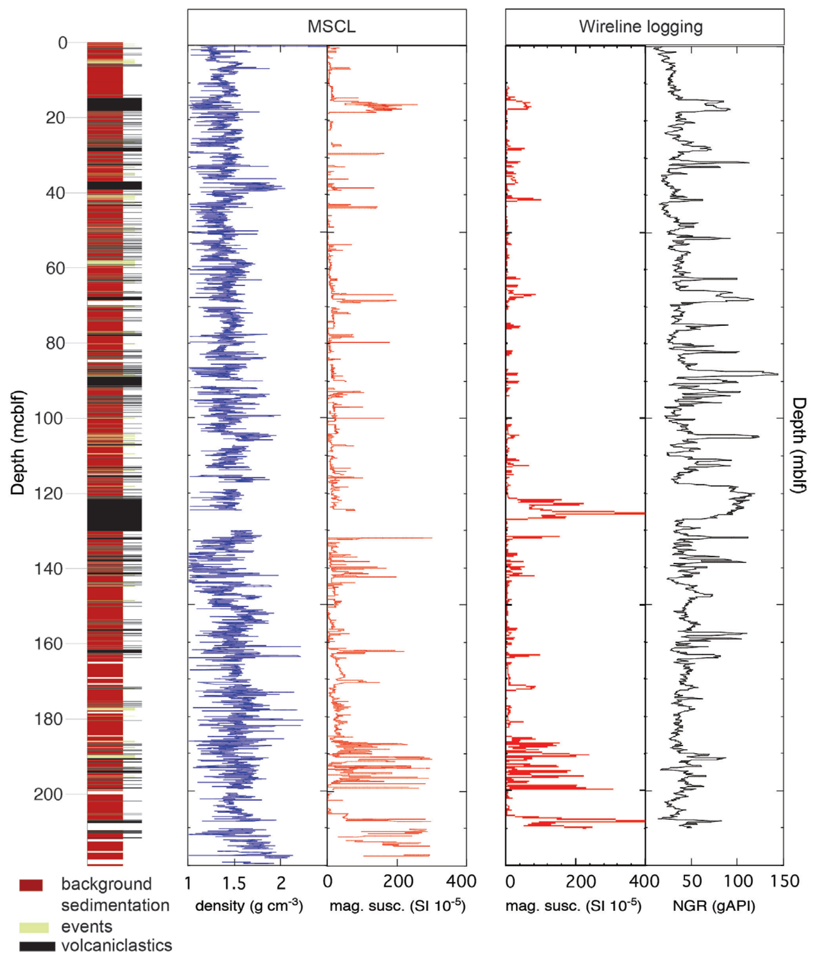

Figure 8. Simplified lithologic log of the Ahlat Ridge composite section (on the basis of visual core descriptions after core opening) distinguishing background sediments (laminated or banded), volcaniclastic layers and event layers (e.g., turbidite deposits or other mass-movement related deposits). Log is juxtaposed to multisensor core logger (MSCL) data (wet bulk density, magnetic susceptibility) and, on the independent logging depth scale, magnetic susceptibility and natural gamma ray (NGR) as measured by the wireline tools. Note good match between volcaniclastic layers and high magnetic susceptibility and gamma ray values. Note also how wireline logging magnetic susceptibility matches MSCL data and is able to fill gaps of low core recovery. Core-based data plotted in meters composite below lake floor (mcblf), wire-line logging data in meters below lake floor (mblf).

Drilling Operations

Core Drilling and Recovery

The ICDP drilling operation was carried out from 2 July to 23 August 2010. As operator of the deep drilling, the U.S. corporation DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust) developed and assembled a new Deep Lake Drilling System (DLDS). It was specifically designed for coring sediments from deep lakes, and it made its maiden voyage on Lake Van. The DLDS consists of two main parts: the barge and the drilling rig. The barge is a modular system constructed with six separate containers connected in a two-by-three configuration (24.4 m long, 7.3 m wide). The drill rig (Atlas Copco T3WDH) is a top-head-drive rotary rig. The platform also accommodates drilling pipes, mud tanks, a science lab, and a driller's shack. In order to securely set the anchors in water depths of more than 400 m, a 2x2 containers large platform was equipped with a hydraulic winch which served as an additional barge during anchoring operations. During the campaign, two drill and two science teams worked in two 12-hour shifts on the platform, and one science team worked in a shore-based lab. During the shift changes, the cores were transported to the shore and stored in a cooling container at 4°C. The DOSECC drill barge operated in Lake Van at water depths of up to 360 m, and cores from sub-lake-floor depths of 140 m (NB) and 220 m (AR) depth were retrieved, the latter reaching the bedrock at the base of the lacustrine succession as predicted by the seismic data. To obtain a complete sedimentary section, the two sites were multiple-cored (Figs. 3, 4). An average recovery of the cored sections of 91% has been obtained at the AR site and of 71% at the NB site. The length of the total recovered cores is over 800 m.

Downhole Logging Operations

Downhole logging was performed in Hole 2D at the AR site (to 212 m depth) and in Hole 1D at the NB site (to 127 m depth). Due to borehole instability, the slimhole tools were lowered into the holes through the drill pipes, and several sections of overlapping 15–105-m-long open hole intervals were measured. Continuous data sets of downhole data (spectral gamma ray, magnetic susceptibility [Fig. 8]; dipmeter, resistivity, and temperature as well as partly sonic data) were achieved at both sites. Additionally, vertical seismic profiling at the AR site was carried out by use of an airgun source and a three-component geophone.

The logging-data quality is high, and in particular natural radioactivity (natural gamma ray, K, U, Th-contents), susceptibility (Fig. 8), and resistivity show strong variations, which are promising for further interpretations. Characterization of the physical properties of the lithologies by use of multivariate statistics (cluster analysis) and comparison with results of the core description is ongoing. Of particular interest are variations of physical properties within the tephra deposits, which will be linked to volcanic composition and volcanic source.

Onsite Laboratory Analyses

MSCL Core Scanning

First core analyses were performed in an onshore laboratory in a 24-hour fashion, following the general concept utilized in similar drilling projects (Melles et al., 2011, 2012; Ohlendorf et al., 2011). A multisensor core logger (MSCL) measured all recovered core sections and yielded wet bulk density, magnetic susceptibility, and p-wave velocity data at a vertical spacing of 1 cm (Fig. 8). These data were used to establish a rough composite section between the different holes at each site, so that drilling operations could be guided in real time in order to have as few gaps as possible in the final composite section. Correlations between the sites were communicated directly to the drilling platform, where presumed overlaps between previously drilled cores were taken into consideration when deciding ideal overlapping drives for the ongoing coring operations. The minimal number of gaps of the resulting composite section (Fig. 8) reflects the usefulness of this critical onsite capability.

Core-Catcher Samples and Pore Waters

The recovered sediment cores were not opened until the core-opening parties at the Integrated Ocean Drilling Program (IODP) Bremen core repository. Core catchers, spaced usually every three meters, provided the available sample material for onsite lithologic descriptions. Smear slides and visual inspections of core-catcher material yielded the first indications of sediment composition, i.e., the distributions of volcanic, detrital, authigenic (carbonate) and biogenic (e.g., diatoms) constituents. The core-catcher samples were also used for initial $^{40}Ar/^{39}Ar$ single-crystal dating of anorthoclase phenocryst analysis focusing on the lower part of the AR site.

Furthermore, core-catcher samples were subsampled for geochemical, pollen, and biomarker analyses and were used for pore-water sampling. Pore water was extracted by hydraulic squeezing, using IODP-style PTFE-titanium squeezers with Teflon disks (Manheim, 1966). Pore-water samples were divided into three aliquots. (1) Salinity and pH values were measured directly in the shore-based lab. (2) One aliquot for major cation measurement was acidified with 2% HNO_3 to prevent mineral precipitation. (3) An aliquot for

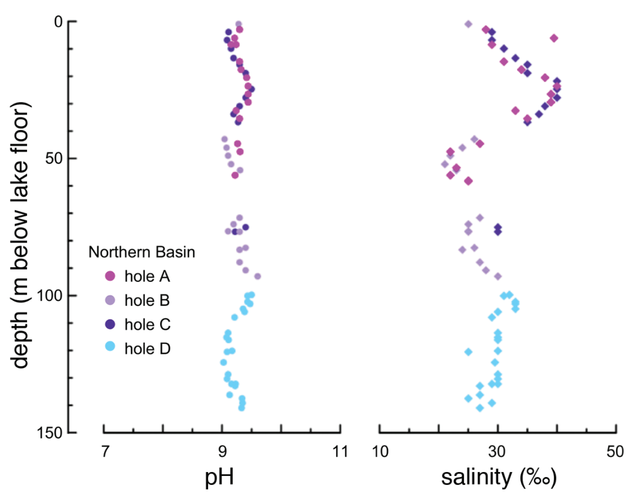

Figure 9. pH and salinity pore water profiles from the Northern Basin analyzed in the on-land lab. Both profiles show distinct “positive” and “negative” fluctuations with regard to recent geochemical state of Lake Van. Observed gradients can only exist over the given temporal (10–100 kyr) and spatial (>20 m) scales if the vertical diffusive transport is suppressed in comparison to diffusive exchange in a continuous and connected pore-water domain. At Ahlat Ridge (not shown), the pore water pH decreases from nearly 10 to 7 in the lowermost 40 m of the cores. According to preliminary results in same depth range, dissolved Ca and Mg concentrations increase continuously—most probably in response to the lower pH—toward the bedrock.

major anions and stable isotope ($\delta^{18}O$, δD) analyses was not preconditioned. Bulk-water anion and cation quantification as well as isotope analysis was carried out in the respective home laboratories.

The measured pore-water pH and salinity profiles (Fig. 9) are in agreement with the lithological analysis, and they add further evidence to the interpretation that Lake Van evolved from a Ca-carbonate dominated freshwater body with a neutral pH to a high-pH Na-carbonate dominated saline water body. Of particular note is the fact that pH and salinity values change within the sediment cores over a length of 20–50 m. Compared to modern conditions, fluctuations towards higher and lower salinity values are observed. The observed salinity (and pH) gradients in the pore-water profiles indicate that the diffusive transport is strongly attenuated in the sediment column of Lake Van. Such limited exchange allows the

Figure 10. The mobile container laboratory BUGLab operated by GFZ Potsdam located at the shore of Lake Van during the ICDP drilling operation.

conservation of the composition of the initial co-deposited lake water in the growing sediment column. These favorable "preserving" conditions offer the unique opportunity to apply the pore-water chemistry as a proxy to reconstruct the geochemical evolution of Lake Van (Tomonaga et al., 2011b, 2012).

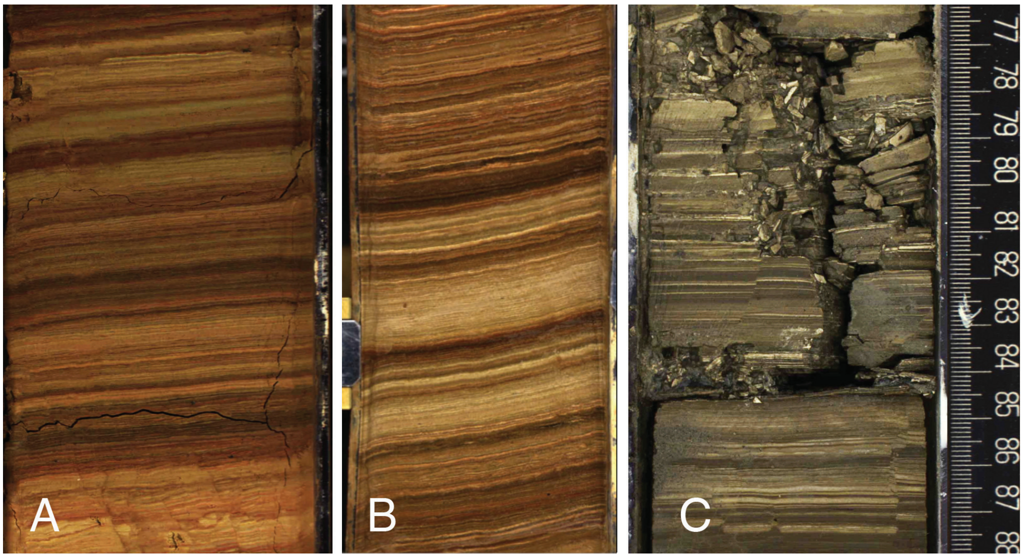

Figure 11. Three examples of finely laminated background deposits from Ahlat Ridge. The example A originates from ~1 m depth and was deposited in the Holocene. Preliminary age data indicates that the example B (40 m depth) can be assigned to the last interglacial (MIS5) and the example C (163 m) to an older interglacial period.

It is interesting that the pore water of the deeper part of the drilled sections at the NB and AR sites shows quite different salinities: 26‰ at the NB and 20‰ at AR site (Fig. 9). These differences suggest that the shallow Northern Basin of Lake Van may have been disconnected from the deep Tatvan Basin during some time in Lake Van's history. Although caution does not allow us to draw any final conclusions at this point, we tentatively speculate that the observed salinity changes reflect mainly climate-controlled lake level fluctuations.

Moreover, the presence of fresher and more neutral pore waters at the Ahlat Ridge site, together with the basal lithologic succession, indicates that Lake Van did not always host saline and high-pH waters. In contrast, the lake may have been born as a common freshwater body. Only later, the lake evolved towards the present saline and high-pH water mass.

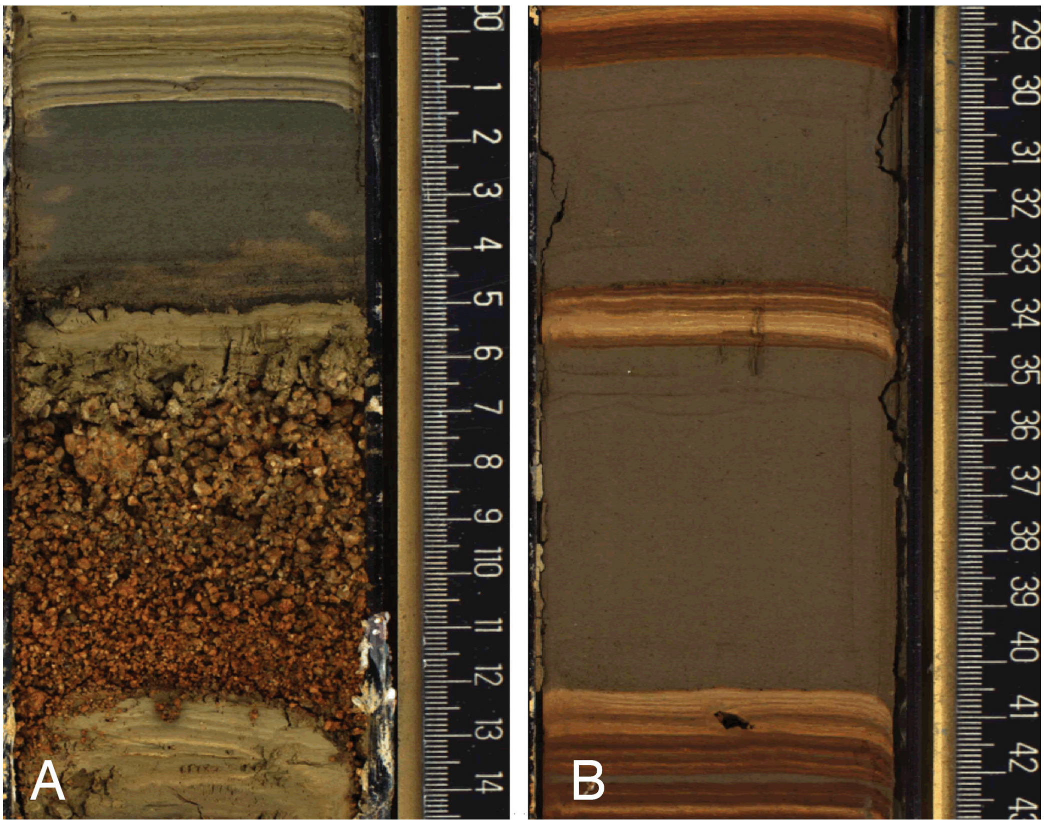

Figure 12. [A] A coarse volcaniclastic layer and a turbidite layer interrupting the continuous, laminated background sedimentation at the Ahlat Ridge site. Note the inverse grading of the pumice particles (deposition from a pumice raft). [B] Two turbidite layers interrupting the laminated sequences (Northern Basin site) consisting mostly of reworked volcaniclastic components.

The indication of limited pore-water exchange means that the dissolved pore-water species, e.g., dissolved noble gases (Blättler et al., 2011; Tomonaga et al., 2011b), may be used to geochemically reconstruct former lake levels and the past ecological state of Lake Van. For this purpose, further pore-water sampling for noble gas analysis was conducted from dedicated core sections of doubled or tripled holes, once completeness of the composite section could be predicted. To achieve these goals, 20–30-cm-long whole-round sections of the cores were sampled immediately after recovery on the drilling platform. At the AR site, ~30 sediment sections were chosen for this purpose and transferred into a specially designed sediment press, which allows the bulk sediment to be squeezed without being exposed to atmospheric air into small copper tube containers for noble gas analysis in the pore water of unconsolidated sediments (Brennwald et al., 2003; Tomonaga et al., 2011a). The ongoing noble gas analysis will give insight on the physical transport mechanisms of crustal and mantle derived fluids through the continental crust and on the evolution of the water exchange and salinity in the open water body of Lake Van (Tomonaga et al., 2012).

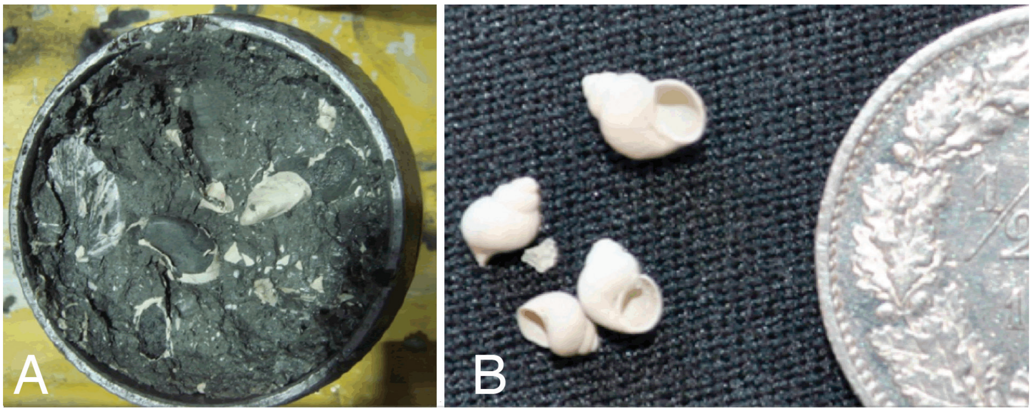

Figure 13. [A] *Dreissena* shells in a core catcher sample just above the sediment-bedrock boundary. [B] Fully conserved and complete shells of *Bithynia*, a freshwater mollusk, found in the sediments at Ahlat Ridge.

Geomicrobial Analyses

Onsite geomicrobiological investigations included cell enumeration, quantification of microbial turnover rates, and pore-water analysis. In order to obtain representative results, it is necessary to subsample and process (incubate, fix) the material immediately after retrieval of the core. For this purpose, we used the mobile geomicrobiology laboratory BUGLab of the GFZ German Research Centre for Geosciences (Fig. 10; see also Mangelsdorf and Kallmeyer, 2010). This container hosts a fully air-conditioned laboratory certified for radioisotope use, and it is equipped with fume hood, working bench, nitrogen gas supply, refrigerator, and freezer for incubation experiments and sample storage. The BUGLab is based on a standard sized 20-ft shipping container, and thus provides a functional, mobile laboratory in almost every environment (shore- or ship-based) as long as sufficient power (230–400 V) is available.

Material from undisturbed core catchers from both drilling sites was used for microbiological investigations. Subsamples for cell enumeration as well as for radioisotope incubation experiments were taken immediately when the core material arrived onshore. Samples for cell enumeration were fixed in artificial lake water including 2% formalin (Kallmeyer et al., 2008). Samples for radioisotope incubation experiments were incubated with 35S sulfate for sulfate reduction rate determination (Jørgensen, 1978; Ferdelman et al., 1997). In addition, individual samples were incubated with ^{14}C-methanol, ^{14}C-bicarbonate, and ^{14}C-acetate for quantification of methanogenesis rates and with ^{14}C-methane for determination of rates of anaerobic oxidation of methane (AOM) (Ferdelman et al., 1997; Treude et al., 2005). All incubations were terminated after 3–5 days, and samples were preserved for analysis in the home lab. Additional samples for quantification of dissolved methane and for pore-water analysis were also taken from the fresh core-catcher material.

Sediment Lithology

The cores were opened in spring 2011 at the IODP core repository located at the MARUM, University of Bremen. The repository's ideal facilities have been used for splitting, photographic and X-ray fluorescence (XRF) scanning of the core halves, core descriptions, and sampling. The recovered lithologies vary as predicted by the results of the pre-drilling seismic and gravity-coring survey; varved or banded lacustrine sediment sections, termed "background deposits" (Fig. 11), are intercalated by volcanic (tephra) and by event layers such as turbidites (Fig. 12). These events appear to be more abundant and thicker in the NB site than at the AR site. The frequent tephra layers guarantee the lithostratigraphic correlation of both sites and constrain the chronological framework of the recovered sediments. The NB site is characterized by much higher sedimentation rate; in fact, the base of the NB site at 143 m can be correlated to ~42 m at the AR site. A composite section has been established at both sites (Fig. 8), representing the best possible complete sediment succession. Whereas the major parts of both drill sites are characterized by one of the three endmember lithologies (background deposits, event and volcanic layers; Fig. 8), the basal unit at AR is characterized by a marked downcore change in lithology. Just above the contact between the

Figure 14. Washed samples of a core catcher of the basal gravel layers. The rounded nature of the gravel indicates coastal or fluvial reworking related to initial lake transgression.

lacustrine sediments and the bedrock, zebra mussel *(Dreissena)* shells, which can only live in fresh or brackish waters, were found within coarse sand and gravel (Fig. 13a). Moreover, perfectly preserved and intact shells of fresh-water gastropods *(Bithynia)* occur at a depth of ~190 m, i.e., ~ 30 m above the basement (Fig. 13b). The presence especially of *Bithynia* shells in the sedimentological record indicates that Lake Van contained freshwater at low pH in the very early days, as confirmed by the pore-water analysis (see above). These basal sediments are underlain by coarse and rounded gravel layers (Fig. 14) indicative of coastal or fluvial origin. Together with the seismic prediction of an acoustic basement at around this depth, these patterns indicate that the drill hole penetrated the initial transgressive phase of Lake Van upon its early creation, and it appears that the retrieved cores hold the entire geological, geochemical, volcanic, seismic, hydrological, and bio-geochemical environmental history of Lake Van starting from its very beginning up to recent. Reaching this basal succession at AR was one of the highlights of the drilling activities as, this boundary marks the birth of Lake Van.

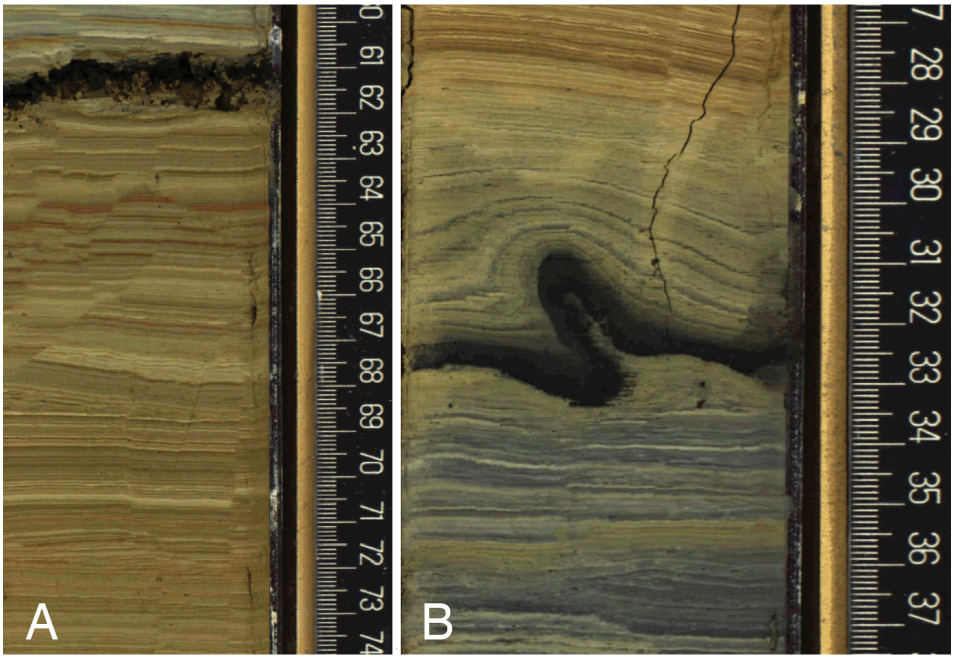

Figure 15. Examples of paleoseismic deformations in the cores. [A] Microfaults dissecting the finely laminated succession. They are only considered of paleoseismic significance if they occur in parallel cores at the same horizons, so that drilling artifacts can be ruled out. [B] Fine tephra layer that has been deformed in a microfold, indicating slumping, potentially induced by seismic shaking.

Paleoseismic Deformation Structures

The partly annually-laminated sedimentary record down to 220 m also contains an invaluable record of past earthquake activities. Various forms of paleoseismites can be easily identified in the finely-laminated sedimentary sequences. Most common are complex multiple microfaults dissecting the laminations (Fig. 15a). Some of them are lined with coarser, mostly volcanic sand grains, which can be explained by liquefaction processes induced by seismic shaking. In addition, several microfolds can be seen (Fig. 15b), reflecting slumping and sliding processes also indicative of seismic shaking. Up to three parallel cores allow us to rank the observed deformation structures in terms of reliability. Deformation structures are often detected in each of the three parallel cores retrieved per site. Such multiple occurrences are used as criteria to interpret seismic shaking as a deformation trigger, as

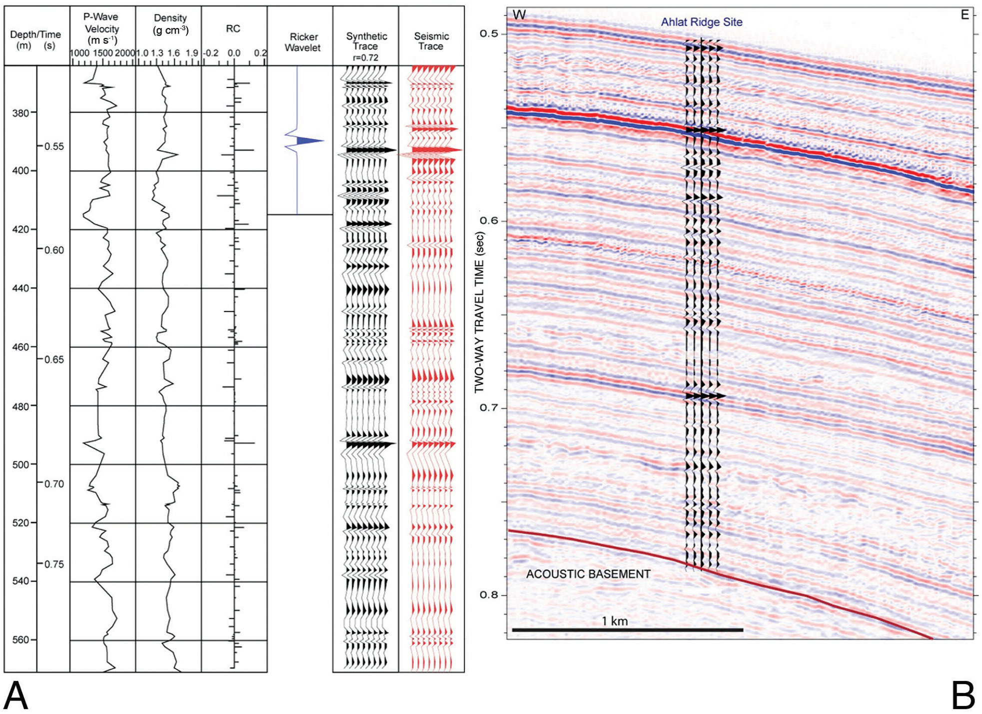

Figure 16. [A] Well to seismic calibration at Ahlat Ridge site. [B] Comparison of the well to seismic tie at Ahlat Ridge site.

single occurrences could also be drilling artifacts. The mapping of these deformation features in the cores will allow us to establish a paleoseismic event catalogue shedding light on recurrence rates and intensities of strong events throughout the past.

In this context, the vulnerability of the area to seismic hazards was dramatically documented by the occurrence of the devastating 2011 M7.2 earthquake near the city of Van.

Integration of Core and Seismic Data

The integration of core data and high-resolution seismic profiles provides a reliable basis for extrapolation of the stratigraphic information over the lake basin. This allows a detailed analysis of the general sedimentary evolution of Lake Van.

Core logging data was used to generate synthetic seismograms for the synthetic-to-well ties that help to obtain two-way travel time-depth relationships at the well locations. This approach aims to extrapolate the stratigraphy from wells to the 3D space by using the seismic data. The SynPAK module (Kingdom Suite software, http://www.seismicmicro.com) was used to construct synthetic seismograms. The results show good correlations between synthetic and real seismic data in both AR and NB sites (Fig. 16). Strong marker horizons correlate well with prominent and dated tephra layers that were also correlated between the two sites. The geologic age data for the drilled horizons will eventually be assigned to the seismic stratigraphic horizons.

Chronostratigraphy

The recovered tephra layers are dominated by Süphan tephras in the deeper sections and Nemrut tephras in the shallower sections. Süphan rhyolitic and dacitic tephras carry plagioclase with low radiogenic yield, while Nemrut tephras are alkaline rhyolites and trachytes carrying anorthoclase as felsic phase. Although physical dating of the deeper part of the section is thus more difficult, preliminary single-crystal argon dating of anorthoclase suggests that the AR record encompasses more than 500,000 years of paleoenvironmental and volcanic/geodynamic history (Sumita et al., 2012). Feldspars in the freshwater basement volcaniclastic sediments are as old as ~16 Ma, reflecting earlier post-collisional volcanism in the area. This general age frame is confirmed by initial geochemical results, as well as pollen analyses, which indicate repetitive changes at the glacial-interglacial scale (Fig. 17). Including the current interglacial stage, four to five interglacial stages can be identified by investigating the lithological pattern, total organic carbon concentrations, and pollen data. Laminated sections rich in total organic carbon and tree pollen are indicative of warmer environments, and they represent marine isotope stages 1, 5, 7, 9, and 11 or 13 that dot the last half million years of paleoclimate history. In contrast, non-laminated sections, poor in organic carbon with higher amounts of steppe plants, are indicative of cold conditions and represent glacial periods.

Outlook on Post-drill Science

A detailed geochronological frame for the long continental record drilled during the PALEOVAN project in 2010 is presently being obtained through varve counting, radiocarbon dating of terrestrial organic matter, $^{40}Ar/^{39}Ar$ single crystal dating of tephra layers, Th/U dating (aragonite laminae), paleomagnetic measurements, ^{10}Be, OSL/TL and orbital tuning/oxygen-isotope stratigraphy. A precise chronology is a precondition for the analysis of the climate signal in the Lake Van record, which has the potential to reveal signals with frequencies higher than Milankovitch cycles such as North Atlantic Oscillation or Dansgaard-Oeschger cycles. These signals will be documented by high-resolution XRF data. Lower frequency signals (Milankovitch) will be investigated through spectral analysis on the downhole logging data so that cyclicities and sedimentation rates can be investigated. Additional information will be obtained through mineralogical, geochemical, and paleontological analysis as well as the analyses of organic material and its composition using biomarkers such as long-chain alkenones, n-alkanes, alcohols, or fatty acids. Reliable reconstructions of Quaternary climate evolution are essential for understand-ing past climate dynamics and for validating general circulation models used to simulate future climate scenarios. Botanical data based on pollen analysis are well established as proxy data, because plants strongly depend on climate, of which temperature and precipitation are decisive factors for the survival and prospering of plants. Botanical-climatological transfer functions will be used for quantitative paleoclimate reconstructions based on the partly annually-laminated sediments of Lake Van for the last >500 kyr. Data-model comparisons are useful to test these results, as shown by Kaspar et al. (2005). In summary, this successful ICDP drilling campaign yielded a rich, temporally long and

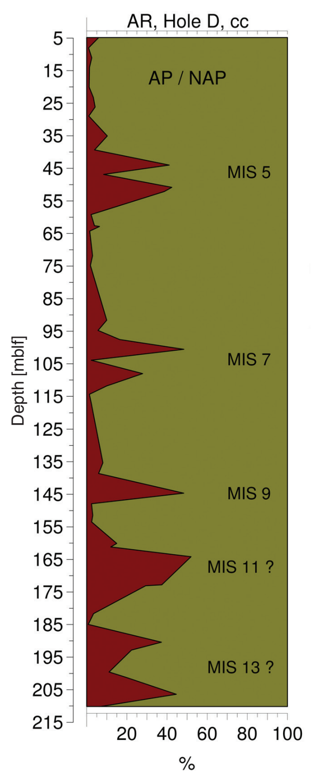

Figure 17. Pollen ratio between trees (arboreal pollen in red: AP) versus herbs (non-arboreal pollen in green: NAP) from Lake Van (AR, hole D, core catcher samples) and tentative correlation with marine isotope stages (MIS).

mostly continuous Lake Van sedimentary succession. This continental record, investigated through a multiproxy approach, has the potential to unravel a large suite of environmental processes occurring in a critical region so far lakking a reliable geological archive of the recent past.

Acknowledgments

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IODP Expedition 326 Operations: First Stage of Nankai Trough Plate Boundary Deep Riser Drilling

by Masataka Kinoshita, Harold Tobin, Nobuhisa Eguchi, and Simon Nielsen

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Introduction

Expedition 326 Ultra Deep Riser Top Hole was the first stage of drilling and coring of the Integrated Ocean Drilling Program (IODP) Hole C0002F to the boundary zone between the Philippine Sea and Eurasian Plates in the Nankai accretionary margin, one of the main objectives of the Nankai Trough SEIsmogenic Zone Experiments (NanTroSEIZE) Complex Drilling Program. The expedition objectives were purely operational, with the goal being installation of the wellhead assembly and drilling and casing the uppermost 800 m of the planned 7-km deep hole. Accordingly, no science party was on board during the expedition, and no scientific results are reported. Scientific objectives for the top 1400 m of this Site were previously fulfilled during NanTroSEIZE Stage 1 Expeditions 314 and 315 (Kinoshita et al., 2009).

After a one month operation in July–August 2010, Hole C0002F had been drilled to 872.5 m below sea floor (mbsf), and the hole was lined with cemented-in 20-inch casing. A corrosion cap was set in preparation for return to continue drilling in 2012. We confirm that Hole C0002F is now ready for deep riser drilling to the plate boundary fault zone.

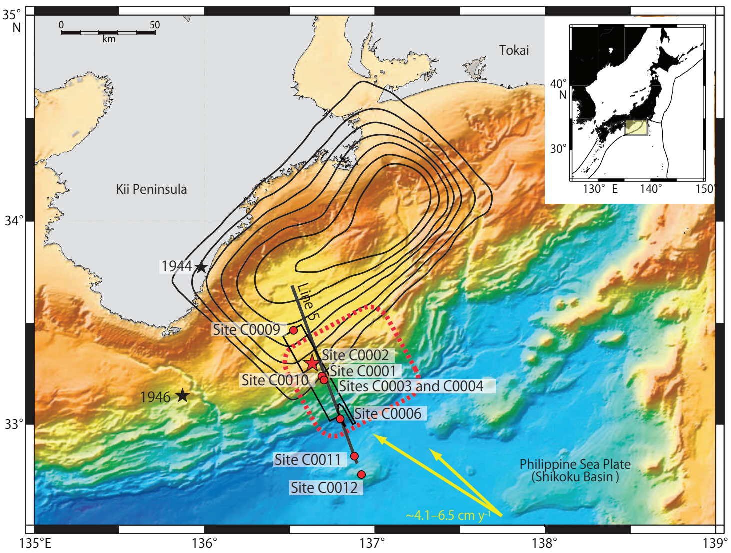

Figure 1. Map of Nankai accretionary complex off Kumano, showing NanTroSEIZE drill sites. Yellow arrows=computed far-field convergence vectors between the Philippine Sea Plate and Japan (Seno et al., 1993; Heki, 2007). Contours indicate estimated slip during the 1944 event (0.5-m intervals). Red box outlines region of recorded very low frequency events (Obara and Ito, 2005). Red circles=NanTroSEIZE drill sites. C0002 is marked with a red star.

NanTroSEIZE Complex Drilling Project

NanTroSEIZE is a multiexpedition, multistage IODP drilling program focused overall on understanding the mechanics of seismogenesis and rupture propagation along subduction plate boundary faults (Tobin and Kinoshita, 2006). This program includes a coordinated effort to characterize (through integrating core/log with seismic images), sample (core/cuttings), and instrument (borehole observatory) the plate boundary fault system near the updip limit of the locked zone of Tonankai great earthquakes at 5–7 km below seafloor (Figs. 1, 2; Tobin and Kinoshita, 2006).

The main objectives are to understand (1) the mechanisms controlling the updip aseismic–seismic transition along the megathrust fault systems; (2) processes of earthquake and tsunami generation and strain accumulation and release, including the role of recently discovered slow slip and very low frequency earthquake (Ito and Obara, 2006); (3) the absolute mechanical strength of the plate boundary fault and its degree of interseismic locking; and (4) the potential role of a major upper plate fault system (termed the “megasplay” fault) in seismogenesis and tsunamigenesis. This drilling program approaches these objectives through a combination of riser and riserless drilling, long-term observatories, and associated geophysical, laboratory, and numerical modeling efforts.

At Nankai Trough, high-resolution seismic reflection profiles clearly document a large out-of-sequence thrust fault system (the megasplay fault, after Park et al., 2002) that branches from the plate boundary décollement close to the updip limit of inferred coseismic rupture in the 1944 Tonankai M 8.2 earthquake (Fig. 1). Several lines of evidence indicate that the megasplay system is active and may accommodate a significant fraction of plate boundary motion (Moore et al., 2007, 2009). However, the partitioning of strain between the lower plate interface above the oceanic basement and the megasplay system is not understood, and neither are the nature and mechanisms of fault

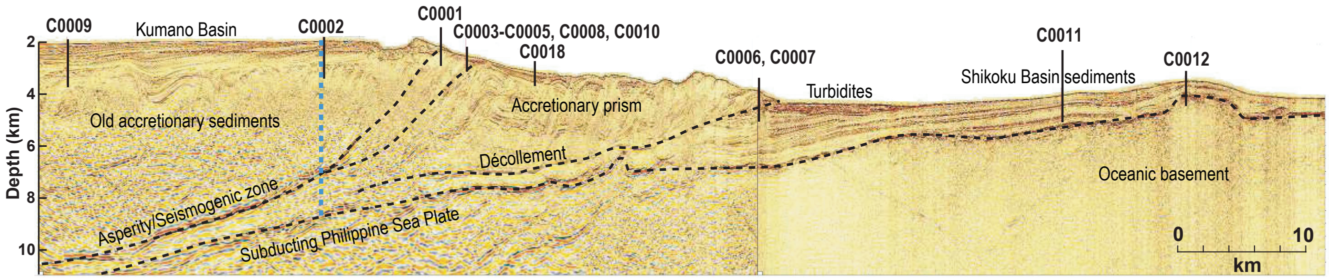

Figure 2. Spliced composite profile of a representative depth section from the NanTroSEIZE 3D seismic data volume (Moore et al., 2009) and Line 95 from IFREE mini-3D seismic survey (Park et al., 2008). Projected positions of Stage 1 and 2 drilling sites, including C0009, C0010, C0011, and C0012.

slip as a function of depth and time on the megasplay. One of the first-order goals in characterizing the seismogenic zone along the Nankai Trough—and which bears on understanding subduction zone megathrust behavior globally and on defining tsunami hazards—is to document the role of the megasplay fault in accommodating plate motion (both seismically and interseismically) and to characterize its mechanical and hydrologic behavior.

IODP Site C0002 is the centerpiece of the NanTroSEIZE project, intended to access the plate interface fault system at a location where it is believed to be capable of seismogenic locking and slip, and to have slipped coseismically during the 1944 Tonankai earthquake. The primary targets include both the basal décollement and the reflector known as the "megasplay fault" (Tobin and Kinoshita, 2006). The megasplay fault zone and the accretionary prism domain are the location of a newly identified class of earthquakes known as very low frequency () earthquakes (Ito and Obara, 2006) as well as the first observation of shallow tectonic tremor (Obana and Kodaira, 2009). The megasplay fault reflector lies at an estimated depth of 5000–5200 mbsf, and the top of the subducting basement is estimated to lie at 6800–7000 mbsf (Fig. 3).

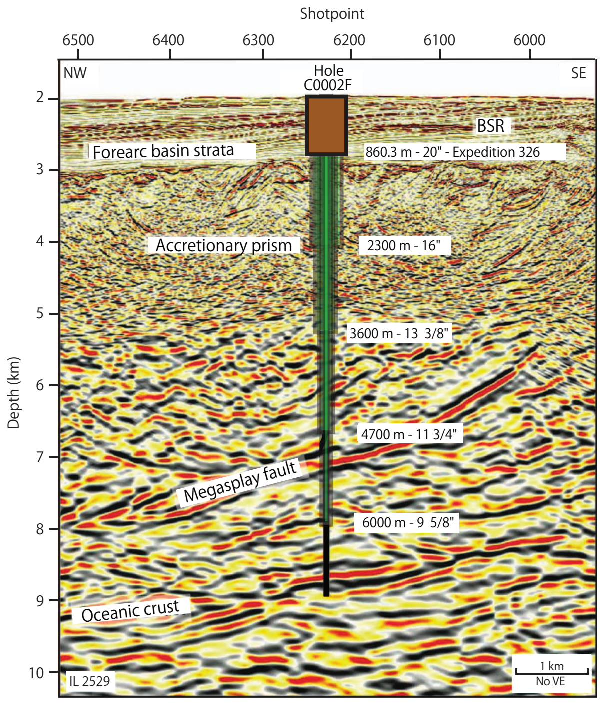

Figure 3. Seismic section of In-line 2529, showing the current status and planned trace for the deep riser Hole C0002F. Brown rectangle denotes the progress made by Expedition 326. Note that the operational options shown here in green are only suggested by the Project Management Team (PMT). BSR=Bottom Simulating Reflector, LWD=Logging-While-Drilling.

During Expedition 314, Site C0002 was drilled to 1401 mbsf with *in situ* measurement of physical properties and borehole imaging through logging while drilling (LWD) but no coring (Expedition 314 Scientists, 2009). Several months later, portions of Site C0002 were cored over the intervals 0–204 mbsf and 475–1057 mbsf on Expedition 315 (Expedition 315 Scientists, 2009). Lithostratigraphy at Site C0002 is characterized by turbiditic sediments to ~830 mbsf, underlain by older rocks of the accretionary prism and/or early slope basin sediments deposited prior to the development of the megasplay fault.

Further background, objectives, and accomplishments to date for the NanTroSEIZE project are discussed in Tobin et al. (2009), Expedition 319 Scientists (2010), and Underwood et al. (2010).

Summary of Operations at Site C0002 Ultra Deep Riser Top Hole

The Expedition 326 was carried out during 19 July to 20 August 2010. Hole C0002F is located at 33° 18.0507′ N, 136° 38.2029′ E (Fig. 4) and its water depth is 1968 m. Total drilling depth was 872.5 mbsf.

Our drilling plan for Expedition 326 was to run a mudmat (a steel plate deployed on the seafloor) and a Guidelineless Reentry Assembly (GRA) to the seafloor, and jet in 36-inch conductor casing to 60 mbsf (Fig. 5). The 36-inch conductor pipe and jetting Bore Hole Assembly (BHA) were made up and run, and by 21 July the guide horn was installed, and the vessel started drifting to site. Hole C0002F was spudded on 25 July, jetting the 36-inch conductor pipe in to 54 mbsf. After the casing angle was confirmed by Write Remotely Operated Vehicle (ROV) to be within 1.5° of vertical, the

BHA was exchanged to a 26-inch drill-ahead assembly. Releasing the Drill Ahead Tool (DAT) went smoothly, followed by drilling with 26-inch bit to target depth of 856.5 mbsf on 27 July.

The subsequent wiper trip encountered a few tight spots, including one too close to total depth (TD) that could endanger the cement job for the casing operation. We decided to deepen the hole slightly, to reach a more stable interval at 868.5 mbsf. By 30 July we were able to clear the hole and move upstream to prepare for casing operations.

The lowering of the 20-inch casing began on 31 July, and by 1 August deep sea drilling vessel (D/V) *Chikyu* could drift back towards Hole C0002F with 72 joints of 20-inch casing trailing underneath. However, during the afternoon of 1 August, probably due to a sudden intensifying of the current, the string sheared off just above the Casing Running Tool (CART), and most of the casing was lost on the seafloor. The decision was made to return to the port of Shingu to load up new casing and try again.

The port call lasted less than a day, and by 3 August *Chikyu* returned to sea to stand by, while decisions were made on shore about how to proceed. It was decided to procure a sturdier but untested CART, which was delivered by the supply boat on 7 August. While decisions were still being made onshore, we surveyed current conditions with the help from the tanker ship *Heisei-maru*. Currents sometimes exceeded 4 knots, with an average around 3 knots.

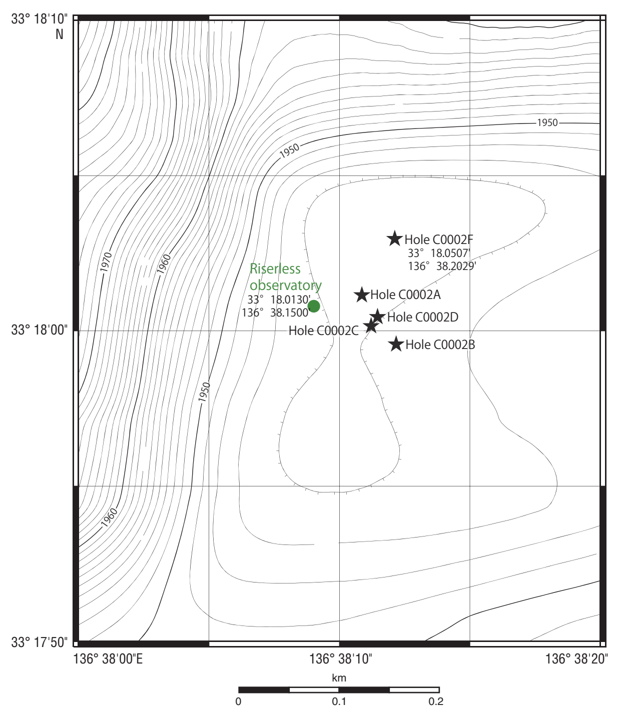

Figure 4. Bathymetric map of Site C0002. Black stars=holes drilled, green circle=proposed hole for Expedition 332 riserless observatory.

Preparations for the second casing operation were completed by 12 August. We reamed down another 4 m (to 872.5 mbsf) and continued wiper trips until 14 August, then returned upstream to a low current area to prepare for setting casing. On 15 August, the new casing was lowered, with four ropes attached to the drill pipe to reduce the Vortex-Induced Vibration (VIV). Use of the rope is proven very effective to suppress VIV (Kitada et al., 2011), thus this option was adopted for the second casing operation.

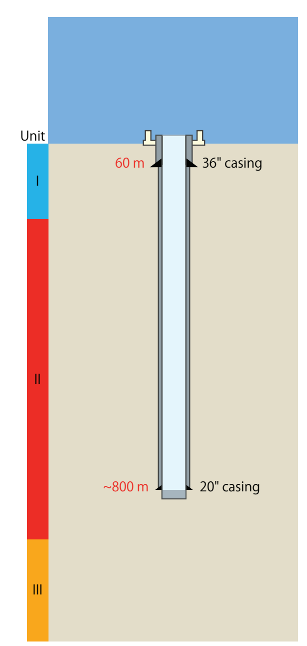

Figure 5. Casing plan for top hole portion of the riser hole, C0002F. The 36-inch conductor casing was set at 54 mbsf, and the 20-inch casing was run to 856.6 mbsf.

Drifting downstream was successfully followed by the casing stabbed into Hole C0002F under the current speeds of >4 knots. On 18 August, the casing was successfully set and cemented, and the drill pipe could be tripped back up. The casing shoe is at 860.3 mbsf. Finally, a steel lid, called the "corrosion cap", was set at the top of the hole by the ROV on 19 August. This completed mission of Expedition 326 to set the wellhead, 36-inch conductor, and 20-inch casing, and to cement to 860.3 mbsf, satisfying the requirement for this tophole portion of the planned riser borehole. The *Chikyu* arrived in Shimizu, Japan, and Expedition 326 concluded on 20 August 2010.

The loss of a substantial length of 20-inch casing in the water column, presumably due to the strong current and VIV, was a costly problem. However, the lesson learned about how to deploy casing and other pipe through the Kuroshio current using the vibration-dampening rope coils proved to be successful in the second attempt.

Plan Toward the Completion of Hole C0002F

In October 2012, Hole C0002F will be revisited to extend the hole from ~900 mbsf to 3600 mbsf during IODP Expedition 338 "NanTroSEIZE Plate Boundary Deep Riser – 2" (Fig. 3). The proposed extension would access the deep interior of the Miocene accretionary prism. In addition to continuous cutting analyses, mud-gas and logging while drilling (LWD) data will be acquired throughout the interval, whereas the core sampling is planned for a limited interval (2300–2400 mbsf). The hole will be cased with

16-inch casing for the upper 2300 m, then with 13 3/8 inch casing down to 3600 mbsf.

In the following year, this hole is planned to be deepened to ~4700 mbsf for the next casing, followed by the drilling/coring ahead toward the megasplay fault system that is expected at 5000–5200 mbsf.

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The IODP Expedition 332 : Eyes on the Prism, The NanTroSEIZE Observatories

by Sean T. Toczko, Achim J. Kopf, Eiichiro Araki, and the IODP Expedition 332 Scientific Party

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Abstract

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a major long-term drilling project designed to investigate the seismogenic behavior of subduction zone plate boundaries. Integrated Ocean Drilling Program (IODP) Expedition 332 deployed a long-term borehole monitoring system (LTBMS), an advanced Circulation Obviation Retrofit Kit (CORK)-type observatory. The recovery of pressure and temperature data from a temporary observatory (SmartPlug) deployed during IODP Expedition 319 helped prove the SmartPlug concept. The permanent LTBMS was deployed n the upper 1000 m of Site C0002, while the SmartPlug was recovered from Site C0010 and replaced with a more capable "GeniusPlug", incorporating an extension with a geochem-ical sampler and biological experiment to the original SmartPlug design. SmartPlug pressure and temperature data showed signs of transient pressure events.

Introduction

Subduction zones account for the majority of global seismic moment release, and slip along subduction megathrusts generate both damaging earthquakes and tsunamis. Understanding the processes that govern the distribution, mechanics, and style of slip along subduction and other plate boundary fault systems is essential to earthquake and tsunami hazard assessment. NanTroSEIZE is a multi-expedition, multistage IODP drilling project focused on understanding the mechanics of subduction plate boundary faults (Tobin and Kinoshita, 2006). The drilling program includes a coordinated effort to characterize, sample, and instrument the plate boundary system at several locations offshore of the Kii Peninsula (Fig. 1), culminating in drilling, sampling, and instrumenting the plate boundary fault system near the updip limit of inferred coseismic slip, at 5~7 km below sea-floor (Fig. 2; Tobin and Kinoshita, 2006) and in installation of a distributed network of integrated borehole observatories to monitor strain and seismological, thermal, and hydrological processes.

In the NanTroSEIZE study area, high-resolution seismic reflection profiles across the outer rise clearly document a major out-of-sequence thrust fault system (megasplay fault, after Park et al., 2002) that branches from the décollement close to the updip limit of inferred coseismic rupture in the 1944 Tonankai M 8.2 earthquake (Fig. 2). Several lines of evidence indicate that the megasplay system is active, may accommodate a significant fraction of plate boundary motion, and may slip coseismically (Moore et al., 2007; Strasser et al., 2009). However, the partitioning of strain between the lower plate interface (the décollement zone) and the megasplay system and the nature and mechanisms of fault slip as a function of depth and time on the megasplay are not understood. Thus, the meg-

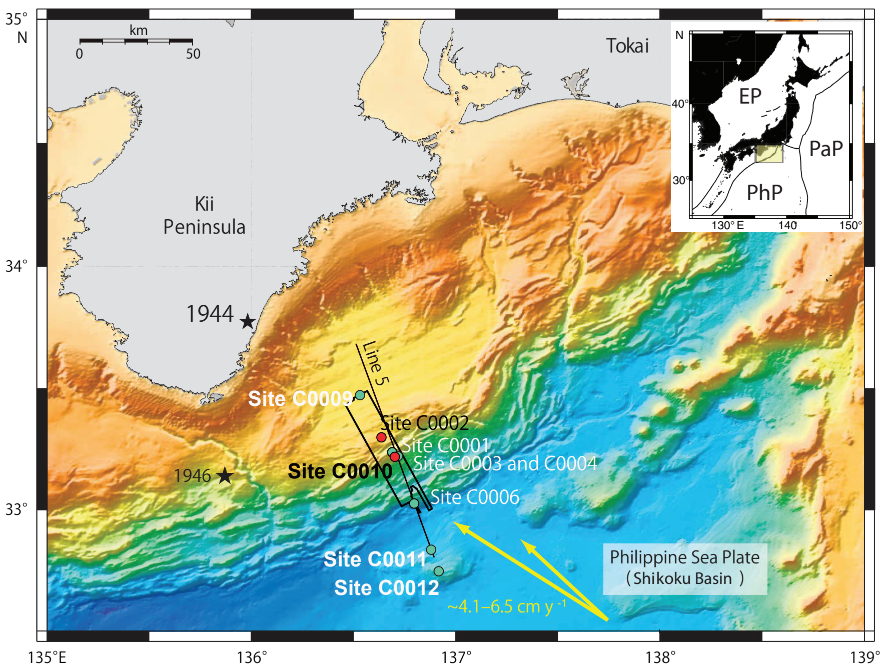

Figure 1. A map of the study area depicting Sites C0002 and C0010 with red circles. The locations of the other NanTroSEIZE sites are shown (green circles), while the inset shows the site location in reference to Japan, and the respective tectonic plates surrounding Japan (EP=Eurasian Plate, PaP=Pacific Plate, PhP=Philippine Plate). The yellow arrows depict the relative movement (4.1–6.5 cm y^{-1}) of the Philippine Plate. The elongated box depicts the limits of the 3D survey area, while Line 5 depicts KR0108-5, a 2D seismic survey line.

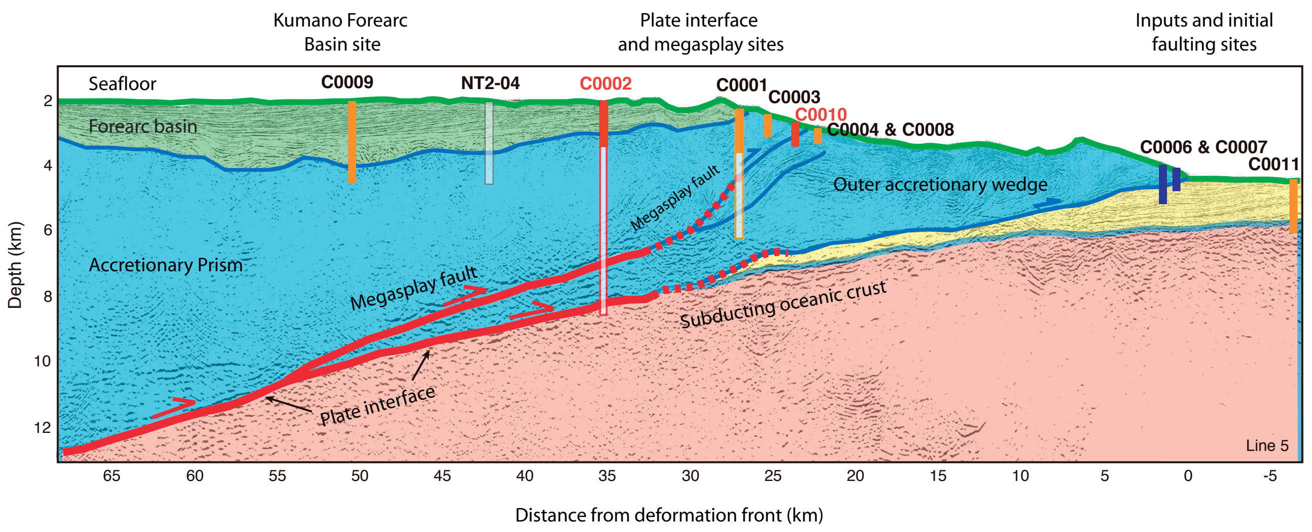

Figure 2. Interpreted seismic profile at regional scale showing interpretation by Park et al. (2002) and NanTroSEIZE drill sites. Sites C0002 and C0010 are indicated in red. All drill sites show current penetration (solid bars) and planned penetration (empty bars).

asplay and the region near its updip terminus comprise one of the primary drilling and monitoring targets for NanTroSEIZE.

NanTroSEIZE Stage 1 included riserless drilling along a transect of eight sites that targeted the frontal thrust region near the trench, the megasplay fault region, and the Kumano forearc basin region (Fig. 2) One of these sites, IODP Site C0002 in the forearc basin, also serves as the ultra-deep riser-drilling target. Expedition 319 installed a temporary borehole observatory (SmartPlug) at Site C0010 in an interval of screened casing across the megasplay fault (McNeill et al., 2010; Saffer et al., 2010).

IODP Expedition 332 continued, expanded, and extended the observatory program, installing the LTBMS and GeniusPlug observatories at Sites C0002 and C0010, respectively.

The Nankai Margin

The Nankai Trough (Fig. 1) is formed by subduction of the Philippine Sea Plate underneath southwestern Japan at a rate of ~4.1–6.5 cm y^{-1} along an azimuth of 300°–315°N (Seno et al., 1993; Miyazaki and Heki, 2001) down an interface dipping 3°–7° (Kodaira et al., 2000). The Nankai Trough subduction zone forms a sediment-dominated accretionary prism. In the toe region, an incoming sedimentary section ~1–1.5 km thick is accreted to or underthrust below the margin (Moore et al., 2001, 2009).

The megasplay is a major structural boundary to the rear of the accretionary wedge; it forms the boundary between the outer wedge and forearc basin, traverses the entire wedge, and has had a protracted history as shown by the tilted forearc basin sediments trapped behind its leading edge (Moore et al., 2007). The megasplay is also hypothesized to represent a discontinuity in rock physical properties and a mechanical boundary between the inner and outer accretionary wedge and between aseismic and seismogenic fault behavior along the plate boundary (Wang and Hu, 2006). At depth, the megasplay is imaged in seismic reflection data as a high-amplitude reflector (Fig. 2; Bangs et al., 2009), and it branches into a family of smaller splays in the upper few kilo-

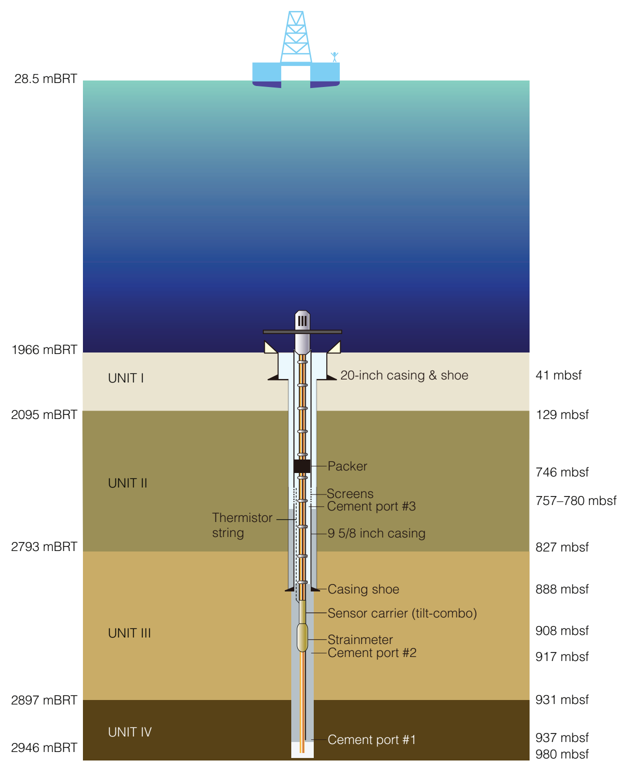

Figure 3. Diagram of the LTBMS installed at Site C0002. The lithological units (Units I–IV) are shown, as well as the depths for different components of the observatory and casing string. Lithological Unit IV is the upper accretionary prism, while Units III to I represents the Kumano forearc basin. (mBRT=meters below rotary table; mbsf=meters below seafloor).

meters below the seafloor, including the fault penetrated at IODP Sites C0004 and C0010. Direct fault intersections to the seafloor are not observed (Moore et al., 2007; Strasser et al., 2009); however, the thrust sheets wedge into these deposits, causing tilt and slumping of even the deposits nearest to the surface. Evidence for mass wasting complexes is consequently found at IODP Sites C0004, C0008, and C0010. Site C0010, as well as Site C0002 further landward in the forearc basin, were the target areas of Expedition 332.

Site C0010, drilled during Expedition 319 (McNeill et al., 2010; Saffer et al., 2010) included Logging While Drilling (LWD) drilling through the megasplay fault zone and into its footwall, setting casing with screens across the fault zone, and installing a simple and temporary borehole observatory (SmartPlug) to monitor fluid pressure and temperature in the shallow megasplay. Major lithologic boundaries as well as the location of the megasplay fault at ~407 mbsf were identified in LWD data and were used to select a depth interval spanning the fault for placement of the two screened casing joints (Saffer et al., 2010).

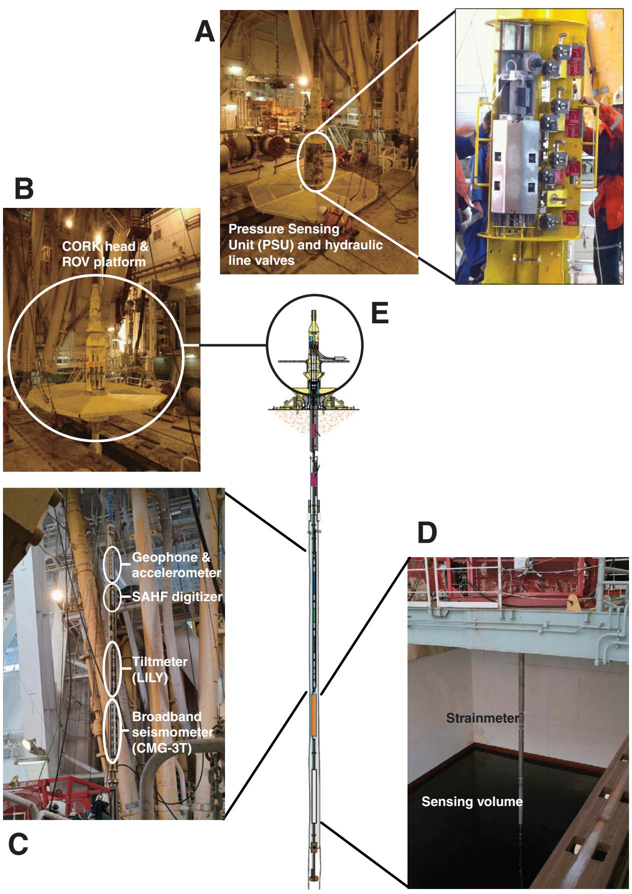

Figure 4. The sensors and placement on the LTBMS CORK observatory at Site C0002. Photos of the different sensor packages and their arrangement on the downhole and CORK head sections were taken during deployment. [A] The Pressure Sensing Unit (PSU), an independent sensor array mounted on the CORK head. [B] CORK head and ROV platform. [C] Sensor carrier, with a geophone and accelerometer assembly, a stand-alone heat flow meter (SAHF) digitizer for the thermistor string, a LILY tiltmeter, and a CMG-3T Guralp seismometer. [D] Strainmeter and sensing volume. [E] Diagram of the Site C0002 CORK observatory.

Site C0002 is located near the southeastern edge of the Kumano forearc basin (Fig. 2). Expedition 332 revisited Site C0002 and drilled with a limited suite of LWD/measurement-while-drilling (MWD) tools for reconnaissance and to identify the most suitable depth intervals to place the sensors of the LTBMS.

NanTroSEIZE Observatories and IODP Expedition 332

Expedition 332 operations at Site C0010 involved recovering the SmartPlug installed during Expedition 319 and replacing it with an expanded GeniusPlug Observatory. Operations at Site C0002 were the first steps in one of the two final phases of NanTroSEIZE, in this case, installing a permanent observatory in the upper section of the Kumano Basin, which will in the future have a complementary deep observatory installed down to the plate boundary.

LTBMS Sensors, Site C0002

The LTBMS sensor array (Fig. 3) is designed to collect multiparameter observations covering a dynamic range of events, including local microearthquakes, low frequency earthquakes, and large-scale earthquakes related to the Tonankai plate boundary movement approximately 6 km below the sensor array. The LTBMS observatory is comprised of two main components: (1) downhole sensors and (2) a CORK head unit at the seafloor with a pressure and temperature multi-sensor package and data and power connections to the downhole instruments (Fig. 4). The CORK head assembly pressure sensor unit (PSU) is comprised of four pressure transducers, three of which are connected via two-way valves to individual hydraulic lines to one of three pressure ports downhole. The bottom-hole pressure port (#3) was set below the Unit III/IV boundary to sample pore fluid pressure in the accretionary complex (Unit IV) beneath the Kumano forearc basin sediment (Units I–III). Pressure Port #2 was located inside Unit III at 917 mbsf, just below the strainmeter sensing surface.

The downhole sensor suite comprises a strainmeter, a Guralp broadband seismometer, and a tilt combo (tiltmeter, geophone, accelerometer, and thermometer string digitizer)—all attached to a sensor carrier—and a thermistor string (Fig. 4). The strainmeter, along with the tilt combination package, was set into a fracture-free zone (890–917 mbsf) as identified via LWD drilling within the lower Unit III mudstone layer (Kopf et al., 2011a). This provides the strainmeter with the best possible coupling to a relatively homogenous section of the formation. Above the strainmeter is the instrument carrier (890–908 mbsf), hosting the seismometer and the tilt combo package. The sensor carrier also holds a data digitizer for the thermistor string, with the two uppermost nodes positioned in the screened casing interval and two nodes in the cemented section above the instrument carrier.

It was necessary to isolate the seismic sensors from the possibility of signals being transmitted from the casing above by placing the 9-inch casing shoe above the seismic sensor and cemented section. Therefore, the casing shoe was set at 888 mbsf (Fig. 3), above the top of the instrument carrier, in an interval without significant washouts. This ensures a good cementing zone for the bottom of the casing, which also serves to isolate the screened casing section from Unit III. The screened casing (757–780 mbsf) was set in a mudstone layer in Unit II to compare the pore fluid pressure in sedimentary layers with the accretionary prism in Unit IV. Finally, the swellable packer was set near the top of the screened casing interval to minimize the volume associated with the pressure measurement in pressure port #3, and also set to ensure that the packer sealing surface (~1.5 m) does not overlap with any casing joints.

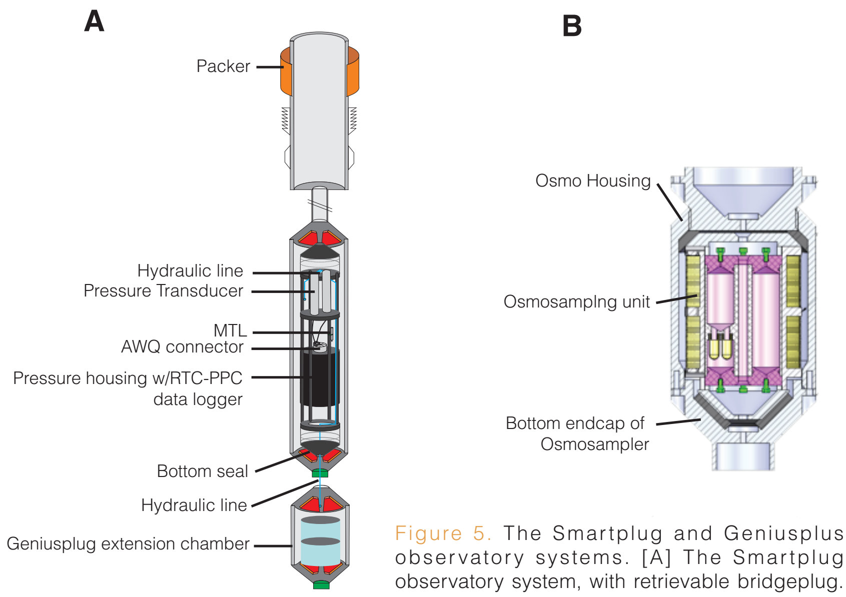

Figure 5. The Smartplug and Geniusplus observatory systems. [A] The Smartplug observatory system, with retrievable bridgeplug. The Geniusplug attachment is shown at the bottom. [B] Close-up and internal diagram of the Geniusplug Osmosampler unit.

The LTBMS CORK in Hole C0002G will provide a wealth of valuable data and observations once it is tied into the DONET seafloor cabled network.

SmartPlug Data Set and GeniusPlug upgrade, Site C0010

The full data set clearly shows a gradual increase in formation pressure and a subtle decrease in the seafloor reference pressure after installation but an overall increase in excess pore pressure. Regardless of this trend, three different types of transient pressure excursions were observed:

1. pressure pulses of up to several hundred pascals in sudden amplitude change relative to background that lasted for 20–60 minutes, which are largely associated with known teleseismic events;
2. tremor-like signals of a fraction of a kilopascal with durations of hours or even days, which can be associated with atmospheric and oceanographic events such as low-pressure systems, storm waves, and tsunamis; and
3. smaller individual pulses of low amplitude (<1 kPa) that lasted for only minutes, which are tentatively associated with either low-magnitude deformational events in the accretionary complex or at the seafloor.

The data collected from the recovered SmartPlug (Fig. 5) prove to be a complete time series data set covering more than fifteen months (since deployment during Expedition 319), and they validate the concept of affordable, durable, replaceable CORK-like observatories (Kopf et al., 2011b). The upgraded version, the GeniusPlug (Fig. 5), is expandable; it uses an attached chamber (30 cm long) which can host other experiments—in the case of Expedition 332, a long-term geochemical and biological experiment.

Post-Expedition 332 Work

Two papers have been prepared, one focusing on vortex-induced vibration (VIV) mitigation for LTBMS deployment and the other on a preliminary analysis of the SmartPlug pressure and temperature data. These have been added to the proceedings for Expedition 332 (see details in Kitada et al., 2011 and in Kopf et al., 2011a, 2011b).

The LTBMS was due for a service call and hookup to battery source and data storage during the spring of 2011; however, these plans were postponed due to the Tohoku earthquake. The site was revisited during January 2012, and tests were successfully run on all systems. Again, the LTBMS was not hooked to the external power source, this time due to poor weather conditions. Current plans call for the system to be up and running after a remotely operated vehicle (ROV) visit in spring 2013.

Plans for Future Experiments and Temporary Observatory Recovery

In 2013, the LTBMS (Site C0002) will be hooked to the DONET network for real-time monitoring. The GeniusPlug (Site C0010) will need to be recovered before the geochemical and biological samples cycle through the system, particularly for sampling associated with the 11 March Tohoku earthquake. This is planned for the 2012/2013 NanTroSEIZE operations of D/V *Chikyu*.

Acknowledgements

We thank all the crew of the D/V *Chikyu* and all the drilling operations and related personnel, particularly the efforts of the Marine Works Japan technicians and the Mantle Quest Japan onboard personnel who worked to make Expedition 332 such a success. We would also like to express our thanks to Tom Pettigrew of Pettigrew Engineering PLLC, who shared his considerable engineering experience with us.

IODP Expedition 332 Scientific Party

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and the IODP Expedition 332 Scientific Party

CORK-Lite: Bringing Legacy Boreholes Back to Life

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Introduction

An essential aspect of the forty years of deep-sea scientific drilling has been to maximize the scientific return during each expedition while preserving samples for future investigations. This philosophy also extends to borehole design, providing the community with tens of cased legacy boreholes that penetrate into the basaltic crust, each ripe for future investigations of crustal properties and experiments to determine crustal processes (Edwards et al., 2012a). During Integrated Ocean Drilling Program (IODP) Expedition 336 to North Pond on the western flank of the Mid-Atlantic Ridge at 22°N, Hole U1383B (Fig. 1) was planned to be a deep hole, but was abandoned when a 14.75-inch tri-cone bit catastrophically failed at 89.9 meters below the seafloor (mbsf) (Expedition 336 Scientists, 2012). This resulted in about 36 meters of open hole below casing, similar to conditions within tens of legacy boreholes. Because the overall experiment required a return to the "natural" hydrologic state in basaltic basement, it was critical to seal the hole to prevent a hydrologic "short circuit". Thus, a plan emerged at sea to seal Hole U1383B with a simplified Circulation Obviation Retrofit Kit (CORK) termed "CORK-Lite" that could be deployed by a remotely operated vehicle (ROV) on a planned dive series five months later. To prepare for this deployment, a standard ROV platform that is used with CORKs was modified to be self-guiding in the re-entry cone and deployed. The next step was to design a CORK system that could seal the borehole, yet be physically manageable with an ROV, and be ready for shipping and deployment within three months. Several key functional aspects dictated the design of the new CORK-Lite (Table 1).

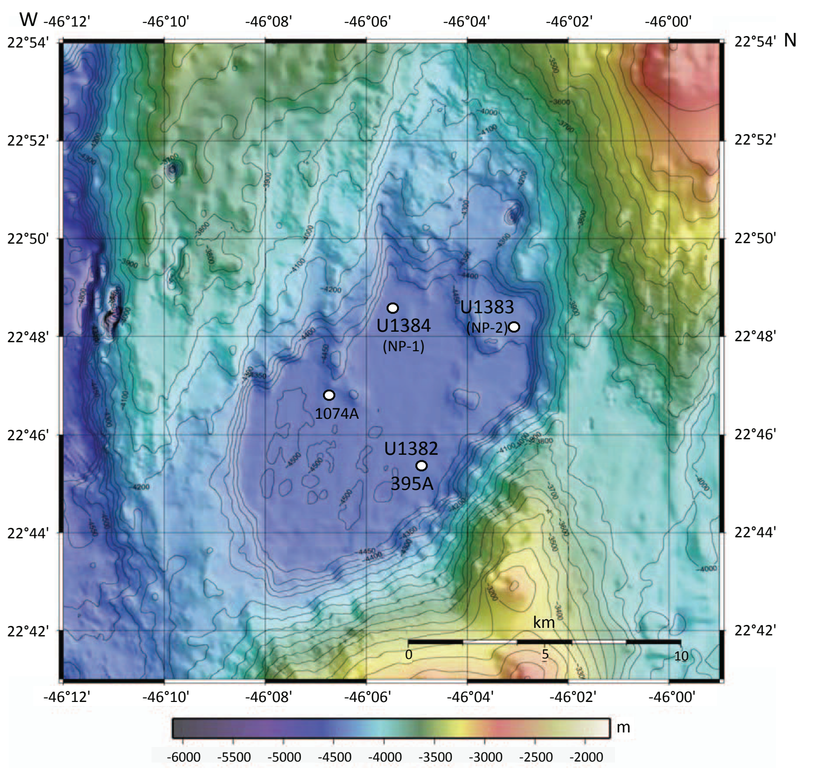

Figure 1. Location of IODP Sites drilled during Exp. 336 (North Pond) and ODP Hole 1074A (duplicated from Expedition 336 Scientists, 2012). The CORK-Lite was deployed at Site U1383. Bathymetry was provided by Schmidt-Schierhorn et al. (2012).

Design of CORK-Lite

The CORK-Lite has four major components: the body with a seal, a removable cap, a downhole instrument string, and a borehole pressure monitoring instrument. The body is a 4.9-m-long 12-inch pipe with a landing seal ring that has a diameter of 19.5 inches that fits within the 32-inch guide hole in the ROV platform (Figs. 2, 3). The landing seal ring lands on and seals in the 20-inch casing hanger. The body has hooks to hang instruments, two valve bodies that accept hydraulic connectors closed in the horizontal position (Wheat et al., 2011), two flanges (lifting wings) for deployment that also serve to aid in moving the body during ROV operations, and a grooved top ring made of stainless steel to insure a proper seal is achieved with the cap. A re-movable "boot" was designed to fit the bottom of the body to protect it during deployment and to prevent it from penetrating into the sediment during free fall. In addition, a lifting bar assembly was fabricated that connects the body to a float package and eases handling by the ROV.

Table 1. A list of design consideration of CORK-Lite.

•	The CORK-Lite has to be installed using an ROV, with weight being balanced by flotation.
•	The CORK-Lite body must be self-centering, fit within the 16-inch casing, robust enough to withstand ROV operations, and extend ~2 m above the ROV platform for ease of ROV manipulations.
•	The seal must apply for either an over-pressured or under-pressured system.
•	Any negative differential pressure across the top seal cap must be vented prior to eventual removal of downhole instruments.
•	Two valves and ports (for redundancy) must attach to and penetrate the body for pressure monitoring within the borehole.
•	Any instrument string has to fit within the steel pipe used as the CORK-Lite body.
•	For safety, the instrument package must reside within the casing; intakes for fluid sampling must extend into the open borehole in an attempt to get “clean” borehole fluids free of possible artifacts from the steel casing and cement above.

The cap was designed to fit on the top of the body and seal it using a rubber gasket (Fig. 4). In case the borehole formation is over-pressured, four latching dogs are included. These dogs are activated by a mechanical lever system that forces the dogs in place through vertical motion of a floating nut driven by a power screw with attached handle. A two-way valve (closed in the horizontal position) is included in the cap. This valve is necessary to equalize the pressure before removing the cap if the borehole is under-pressured. A pad eye is welded under the cap to attach the downhole instrument string.

The downhole instrument string utilized components from Exp. 336 (osmotic pumps, coils of small bore sample tubing, support rods and various connectors) that were designed for deployment within the 3-inch confines of the Exp. 336 CORKs. With the larger diameter available to the CORK-Lite, seven osmotic packages were coupled into one unit (Fig. 5). These packages include standard, dissolved gas, acid addition, enrichment, BOSS (fluid sampler that is preserved with RNA*later*® for microbial-based analysis), and microbial colonization experiments (Jannasch et al., 2004; Wheat et al., 2011; Orcutt et al., 2010). A frame was designed to hold these packages, protect them during

Figure 2. The CORK-Lite body is lowered over the side of the R/V *Maria S. Merian*. The boot is held in place with a tee handle and secured with a bungie. The lifting bar assemblely is attached to the body with triple-strand polyproplyene rope and floats above. Extra *Alvin* dive weights were attached to the hooks for faster descent.

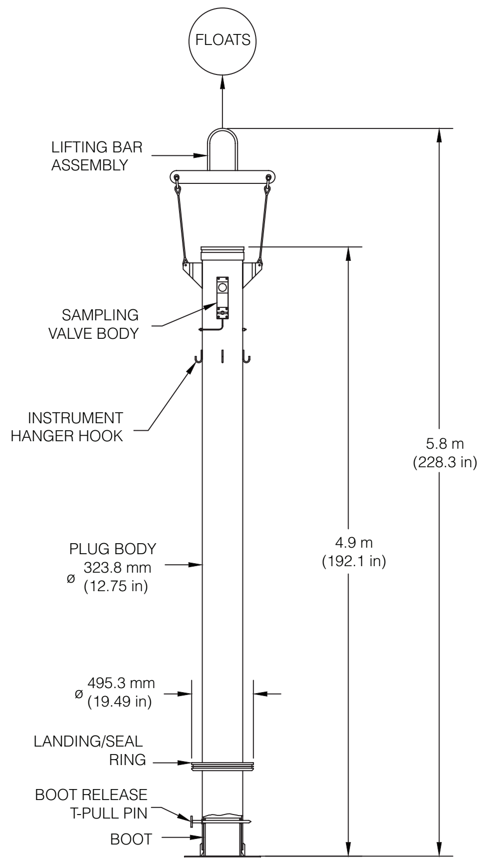

Figure 3. Schematic of the CORK-Lite body during free fall to the seafloor.

deployment and recovery, and guide them into the CORK-Lite body. These frame components have a diameter of 10.75 inches, which easily fit through the 12-inch CORK-Lite body (12-inch I.D.). Because of borehole instability issues within other CORKs, we placed the instrument package near the bottom of the casing yet have the sample intakes extend meters into the open portion of the borehole. Intakes were protected with Tygon tubing and attached to a strength member (rope) and sinker bar. A weak link was positioned just below the instrument package in case the borehole is unstable and traps the sinker bar. Thus, the instrument package can be recovered even if the sinker bar becomes entombed.

The pressure monitoring device was developed at the Pacific Geoscience Centre (Sidney, BC, Canada), identical to most systems deployed on CORKs today, including those deployed on IODP Exp. 336 and previously on Exp. 327 and 328 (see technical descriptions in Davis et al., 2010; Fisher et al., 2011; Edwards et al., 2012b). The instrument includes batteries, electronics, two absolute pressure gauges (Paroscientific Model 8B-7000; one to monitor the formation and the other to monitor the seafloor), a data logger (set to sample pressure and temperature every two minutes like the Exp. 336 CORKs in IODP Holes U1382A and U1383C), an underwater mateable connector (Teledyne ODI), and a stainless steel line that connects to an ROV-deployable hydraulic coupler that fits in the valve package on the CORK-Lite body.

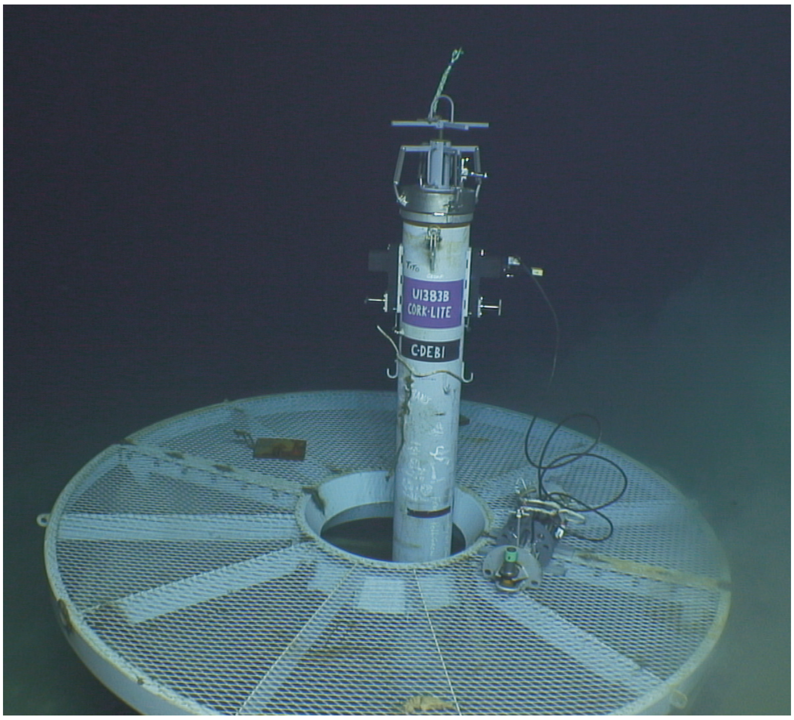

Figure 4. A CORK-Lite was successfully deployed and instrumented in IODP Hole U1383B. The cap (silver material above the gray pipe) is secured to the body utilizing the handle with a short piece of rope that originally was connected to flotation. The pressure logger rests on the ROV platform and is connected to the CORK-Lite body.

ROV Operations

Operations were conducted with the U.S.-operated ROV *Jason* from the German research vessel R/V *Maria S. Merian* during expedition MSM 20/5. The ROV platform was inspected on *Jason* dive J2-623 (20 April 2012). Before the next dive the CORK-Lite body was deployed with ~770 lbs of flotation. During the second dive the CORK-Lite was located, transported to the borehole, and lowered into place. A black stripe was painted on the body prior to deployment and used as an indicator that the body was in the proper position. After the subsequent dive the downhole instrument string was deployed. The instrument string included (from bottom to top) descent weights, a sinker bar, a 12-m-long three-strand polyproplyene rope with a weak link and intakes that extended 8 m from the instrument package, the instrument package (seven OsmoSampler packages, and three self-contained temperature recorders), a 50-m length of 3/8-inch spectra, the top plug, and flotation. The instrument string was located and installed, and the valves were closed. Later in the dive program the pressure logger was attached, and the data set that was retrieved indicated that the CORK-Lite was sealed (Fig. 6).

Figure 5. The downhole instrument package is fabricated before connecting it to the intake and ropes that space the package at the proper depth in the borehole. Seven osmotic packages are arranged in a bundle.

Future Applications

The design, fabrication, and operational effort at Hole U1383B illustrate the engineering potential to seal and instrument any of the tens of legacy boreholes that have been drilled into basement and cased through the sediment, leaving tens to hundreds of meters (in some cases up to 1500 meters) of open borehole (Edwards et al., 2012a).

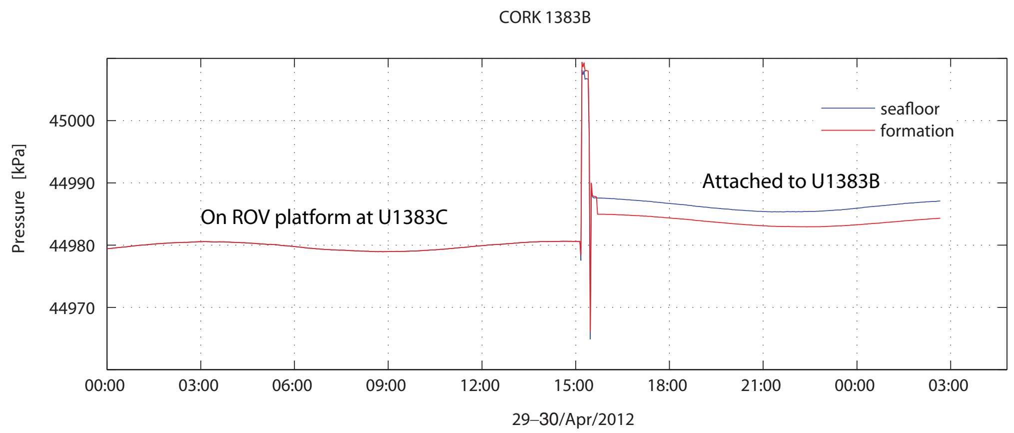

Figure 6. Pressure data from the CORK-Lite at IODP Hole 1383B. Before the instrument was attached, both sensors monitored bottom seawater on the ROV platform at Hole U1383C. After attachment, the two readings are different, signifying that the borehole is sealed and under-pressured relative to bottom seawater.

Placing sensors, samplers, and experiments in legacy boreholes could address a range of fundamental questions about conditions and processes within igneous oceanic crust. For example, the basaltic crustal aquifer plays a substantial role in cooling the Earth, regulating biogeochemical cycles within the oceans, and providing differences in redox potentials (i.e., between oxidizing seawater and reducing basaltic minerals) that offer great potential for abiotic and biologically-mediated electron transfer reactions (Bach and Edwards, 2003; Fisher and Wheat, 2010). With appropriate instrumentation in selected legacy boreholes, we will be able to provide a better measure of the range of biogeochemical processes within the basaltic crust and the global significance of these processes. Legacy boreholes can serve other communities as well, for example, by providing access for a range of sensor suites for geological and geophysical studies.

Because legacy boreholes are typically cased with 10.75-inch pipe or larger, they can accept a range of sensors and instruments that typical CORKs cannot accept (many limit internal instrument diameters to 3.5 inches). Furthermore, there are a number of instrument suites developed by Schlumberger Limited that cannot be used in typical IODP boreholes but could be used in legacy boreholes. Although the initial CORK-Lite did not include electrical cables or an umbilical, future CORK-Lites could be modified to include such connections that penetrate the cap for seafloor interrogation of downhole sensors. Also, it is conceivable to deploy swellable packers, baffles, and other means to eliminate or minimize vertical fluid exchange within the borehole, allowing one to examine specific geologic or hydrologic horizons.

For some applications CORK-Lite provides an inexpensive alternative. It is especially useful for boreholes with single horizons, as it allows for the use of less armored and less expensive umbilicals, and it eliminates the need for an inner casing string or extensive wellhead structure. Furthermore, deploying such systems into legacy boreholes is independent from the drilling schedule. In some ways the CORK-Lite is a rejuvenation of the original CORK concept (Davis et al., 1992), but it is much more versatile. IODP Hole U1383B is just the start! We envision future CORK-Lites that address a range of scientific questions, utilizing a variety of instruments, sensors, and experiments.

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Pressure Core Characterization Tools for Hydrate-Bearing Sediments

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Introduction

Natural gas hydrates form under high fluid pressure and low temperature, where biogenic or thermogenic gases are available. These requirements delimit the distribution of hydrate-bearing sediments to sub-permafrost, deep lakes (>390-m water depth) or ocean sediments (>320 m). Typically, hydrates are found beneath deeper water columns due to thermal fluctuations and diffusion near the sediment surface (Xu and Ruppel, 1999).

The clathrate or cage-like structure formed by water molecules hinders the repulsion between gas molecules allows for very high gas concentration. With the high methane concentration in large areas, natural gas hydrates can become an energy resource and remain a potential source for a potent greenhouse gas. Depressurization and/or warming cause dissociation and volume expansion leading to large-scale sediment destructuration.

A proper characterization of hydrate-bearing sediments requires coring, recovery, manipulation and testing under pressure and temperature (P-T) conditions within the stability field. This report begins with an overview of existing tools, and then describes advances in pressure core technology developed at the Georgia Institute of Technology that have been advanced to address this need.

Pressure Core Technology: Overview

The development of pressure coring and recovery tools have involved research teams around the world, including initiatives such as the International Ocean Drilling Program and the European Union's Marine Science and Technology Program (Kvenvolden et al., 1983; Pettigrew, 1992; Amann et al., 1997; Dickens et al., 2003; Qin et al., 2005; Schultheiss et al., 2009). A depressurization of cores will cause immediate dissociation of gas hydrates. It is therefore necessary to keep the samples at all times under P-T conditions within the stability field. Pressure core manipulation and transfer technology require a longitudinal positioner/manipulator and ball valves to couple components at equalized pressures (Pressure Core Analysis and Transfer System, PCATS; Schultheiss et al., 2006).

Contact testing tools utilizing P- and S-wave velocities, strength, electrical resistivity profiles and internal core temperature (IPTC; Yun et al., 2006), and non-contact tools utilizing gamma density, X-rays and water-coupled P-waves (Pressure Multi-Sensor Core Logger; Schultheiss et al., 2006; Abegg et al., 2008) are avail-able. Subsampling capabilities have also been developed for biological studies under *in situ* P-T conditions (DeepIsoBUG; Parkes et al., 2009).

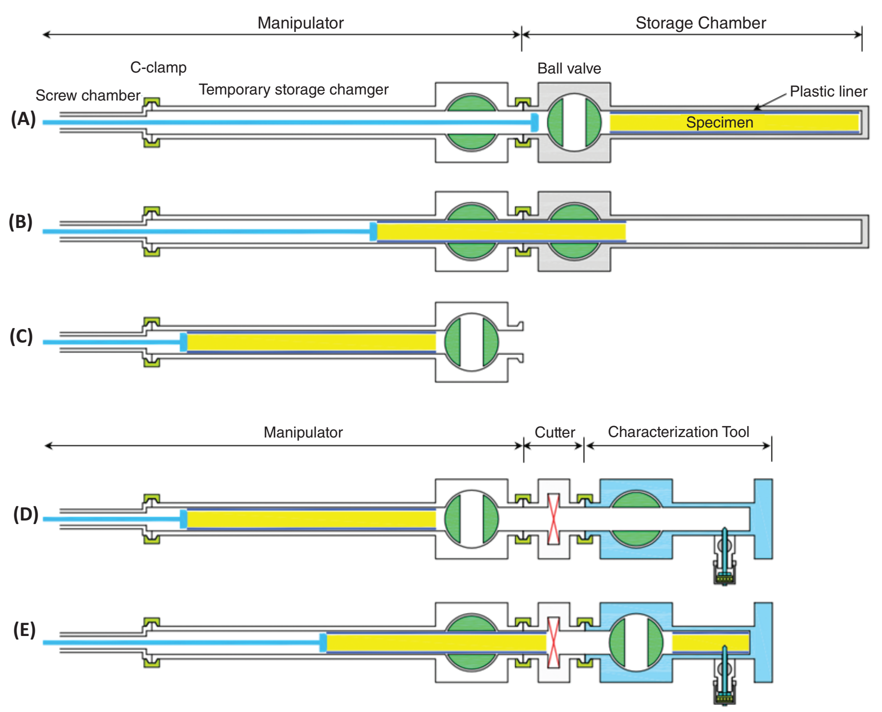

Figure 1. Pressure core manipulation. [A] The manipulator (MAN) couples with the storage chamber, and fluid pressures are equalized at the target pressure p0 before opening the ball valve. [B] The MAN captures the core and transfers it to the temporary storage chamber. [C] Ball valves are closed, and the depressurized storage chamber is separated. [D] The selected characterization tool is coupled to the MAN and is pressurized to $_p0$. [E] Ball valves are opened, and the core is pushed into the characterization tool; stand-alone characterization tools may be detached after retrieving the rest of the core and closing valves. Note: the cutter tool (CUT) is shown in panels [D] & [E]; it is attached in series to cut core to any desired length to meet tool requirements (for stand-alone ESC, DSC, CDC, and BIO tools).

Pressure Core Characterization Tools (PCCTs)

Our pressure core characterization system includes core manipulation tools and characterization chambers. Tools have been selected to obtain complementary information relevant to science and engineering needs, with emphasis on the measurement of parameters used in hydro-thermo-mechanical analyses.

All tools are designed following key guidelines and objectives: simple and robust systems, portable components for fast deployment, modular design for maximum flexibility, standard dimensions and parts for affordable construction and maintenance, rust-resistance for seawater environment, capability of maintaining and operating at pressure, ability to impose effective stress, and safety for monitoring of hydrate dissociation and gas production during controlled depressurization, heating or fluid exchange (such as with liquid CO_2). The modular design allows any two tools/chambers to be coupled through an identical flange-clamp system.

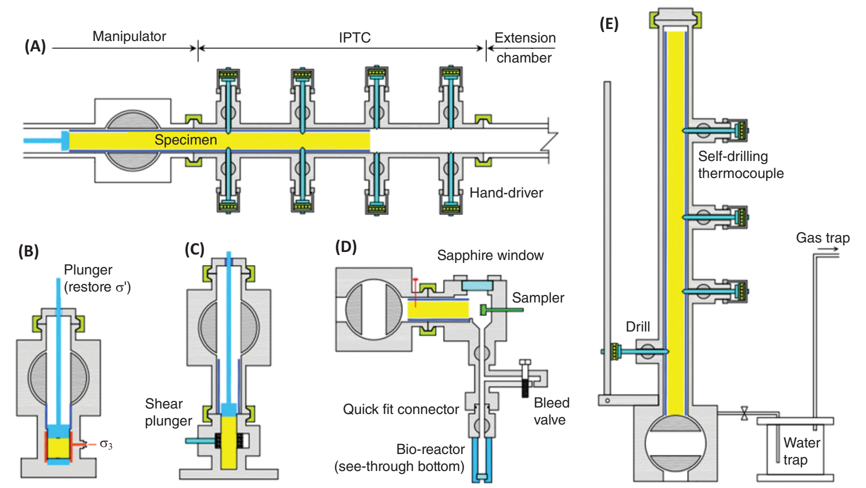

Figure 2. Schematic diagrams of characterization chambers. [A] IPTC with P-T control. [B] ESC with σ'-P-T control. [C] direct shear chamber (DSC) with σ'-τ-P-T control. [D] sampler for multiple bio-reactor chambers (BIO). The outside diameter of the large ball valve shown in all devices is 220 mm. [E] controlled depressurization chamber (CDC) for sediment preservation and gas production.

Manipulator (MAN). The manipulator is a longitudinal positioning system that is used to grab and move the core along the interconnected chambers and valves under the required P-T conditions. Figure 1 shows the typical operation sequence used to retrieve a specimen from the storage chamber into the MAN, followed by displacing the core into a test chamber. The geometric analysis of the operation shown in Fig. 1 reveals that the length of the MAN L_{man} (with its "temporary storage chamber") is proportional to the length of the core L_{core} to be manipulated, $L_{man} \approx 3.5 \times L_{core}$. Our system is designed to handle 1.2-m-long cores (L_{core}); it uses an internal telescopic screw system (stroke=2.6 m) driven by an external stepper motor, and it can position the specimen with sub-millimeter resolution. It is coupled to the 1.3-m-long temporary storage chamber by means of a dismountable flange-clamp connection. A see-through port is included to confirm the position of the MAN at any time.

Sub-sampling. The 1.2-m-long core can be cut into short specimens. Our cutting tool, CUT, houses either a linear or a ring-shaped saw blade within a clamp-type chamber. The saw-based cutting ensures clean surfaces and minimizes specimen disturbance. The CUT is mounted in series between the MAN and any other test or storage chamber as needed (Fig. 1d, 1e).

Instrumented Pressure Testing Chamber (IPTC). The chamber was developed to sample fluids and to measure P- and S-wave velocities, undrained strength, electrical conductivity, and internal core temperature (Fig. 2a; details in Yun et al., 2006). Additional tool developments have been implemented by the USGS, within the context of the Golf of Mexico JIP. This cylindrical chamber has two sets of four diametrically opposite port pairs. The first pair drills holes (ID=8 mm) in the plastic liner so that contact probes in successive ports can be pushed into the specimen. In characterization mode, the IPTC is coupled to the MAN on one side and an extension chamber on the other, and measurements can be conducted at any position along the core length. The eight access ports make the IPTC a versatile chamber for conducting well-monitored production studies in view of reservoir calibration models.

Effective Stress Chamber (ESC). Pressure cores are recovered and stored at fluid P-T conditions needed to preserve hydrate. However, physical properties such as stiffness and shear strength are functions of both hydrate saturation and effective stress, with the relative effective stress increasing as hydrate saturation decreases. The ESC maintains P-T stability conditions and restores the effective stress (σ') that the sediment sustains *in situ* (Fig. 2b). It was designed and laboratory-tested at Georgia Tech in 2006 under Joint Oceanographic Institutions (JOI) sponsorship, and it was first deployed in the field by the Korean Institute of Geoscience & Mineral Resource in collaboration with Geotek (Lee et al., 2009).

The original design was based on a zero lateral strain boundary condition. We have updated this chamber to accommodate a stress-controlled boundary condition using a jacket. The resulting triaxial stress configuration consists of σ_3' applied with the jacket and σ_1' applied by a piston that is advanced through the ball valve and acts directly on the pressure core. The piston and the base pedestal house the sensors needed for the measurements of physical properties, including stiffness (wave velocities), thermal conductivity, and electrical resistivity.

A salient advantage of the flexible wall configuration is the ability to conduct precise fluid conductivity measurements by preventing the preferential flow along the sediment-steel boundaries in rigid wall chambers. This chamber is particularly well suited to monitor production studies under *in situ* effective stress conditions, including assessment of sediment volume change upon dissociation.

Direct Shear Chamber (DSC). Two constraints guided the design of the DSC tool. First, the imperfect boundaries that result when cutting heterogeneous cores under pressure cause stress concentration during vertical loading; thus, we selected a "double direct shear" geometry to cut across the specimen away from end effects. Second, overcutting during coring leaves a gap, and the core tends to tilt during shear; therefore, we adopted a double shear plane configuration to avoid bending action. Consequently, the DSC consists of a thick wall stainless steel ring that is pushed to shear the central third of the specimen (Fig. 2c). The DSC includes the piston to restore effective stress (similar to the ESC), a liner trap to capture the plastic liner before the specimen enters the shear chamber, and a small, lateral built-in frame to push the side piston that displaces the ring (Fig. 2c). The maximum shear displacement (δ_{max}) is 15 mm, allowing both peak and residual shear strengths to be determined. The result is strength and volume change data under *in situ* conditions that are necessary for model calibration, production design, and stability analyses.

Sub-sampling Tool for Bio-Studies (BIO). Assessment of bioactivity in deep-water sediments without incurring depressurization cycles is crucial to the survival of some barophilic microorganisms. The BIO chamber is loaded with a core segment using the MAN; afterwards, it is detached from the MAN for all successive procedures (Fig. 2d). Its operation involves (1) nitrogen-liquid replacement, (2) core face cleaning and chamber sterilization, (3) sub-sampling using a rotary sampling head, and (4) sample deposition into the bio-reactor that is pre-filled with nurturing solutions (volume=10 mL). All operations can be observed through a sapphire window. Bio-reactors are readily replaced by closing a system of two ball valves and decoupling a quick connect fitting. This device allows the collection of a large number of specimens from a single core segment under *in situ* hydrostatic pressure.

Controlled Depressurization Chamber (CDC). Successful pressure coring operations may produce more pressure cores than the available storage. In this case, recovered cores can be selectively depressurized to conduct further studies under atmospheric pressure. The CDC is designed to help preserve the core lithology and to gain valuable in-formation during depressurization, with minimal demand on personnel resources. This stand-alone device has a built-in drilling station to perforate the liner at selected locations in order to reduce the longitudinal expansion of the specimen. A pressure transducer and a thermocouple monitor the gas P-T conditions inside the chamber. In addition, three self-drilling thermocouples are deployed along the CDC; these are driven into the core to monitor the internal sediment temperature during depressurization. Finally, a 2-L water trap and a 55-L gas trap are attached in series to the needle valve that controls the rate of depressurization; these traps allow measurement of the water and gas produced (Fig. 2e).

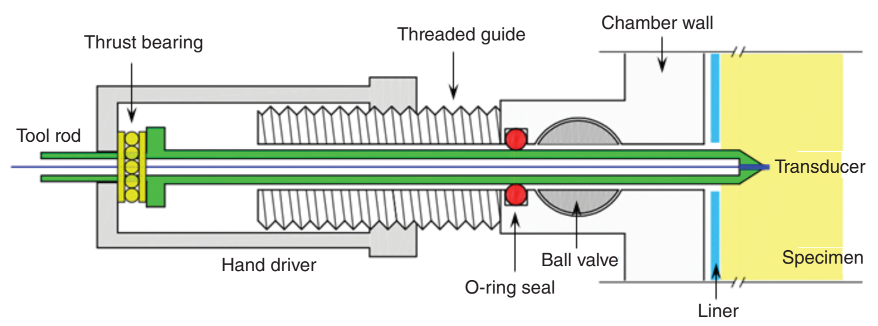

Figure 3. Tool Position. The displacement of sensors, subsampling tools, and drills are controlled under pressure using a screw-based positioning system where the driver advances along the threaded guide while pushing the tool rod (shown in green). Transducers at the tip of the rod are wired through the central hole in the tool rod.

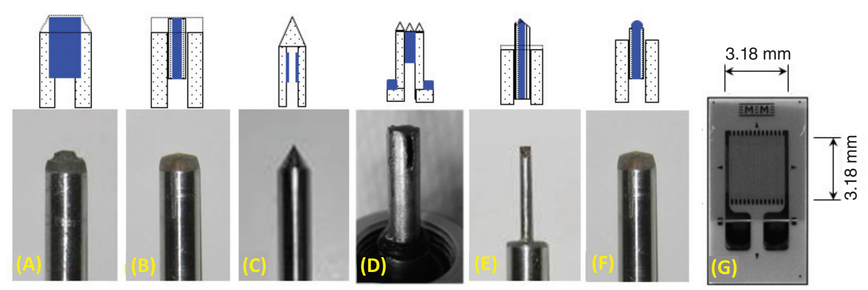

Figure 4. Measurement tools and sensors. [A] Bender elements for S-wave generation and detection. [B] Piezocrystals for P-waves. [C] Penetrometer for strength measurement. [D] Pore fluid sampler. [E] Electrical needle probe for resistivity profiling. [F] Thermocouple instrumented tip. [G] Strain gauge for thermal conductivity determination (TPS–NETL; Rosenbaum et al., 2007).

Measurement of Physical Properties

Multiple sensing systems have been developed to characterize the sediment and to determine hydrological, thermal, chemical, biological, and mechanical parameters within the chambers, under controlled pressure, temperature, and effective stress conditions as described above. Their deployment in the various devices support the comprehensive characterization of natural hydrate-bearing sediments under *in situ* pressure, temperature, and/or stress conditions, and permit detailed monitoring of gas production tests.

Tool Position Control. All contact instruments, sensors, and drills are mounted on polished rods (7.9 mm diameter) that are advanced into the specimen using externally controlled threaded positioning systems to overcome the 1.7 kN force at the maximum working fluid pressure of 35 MPa (Fig. 3). The ball valve between the threaded guide and the chamber permits replacing tools under pressure.

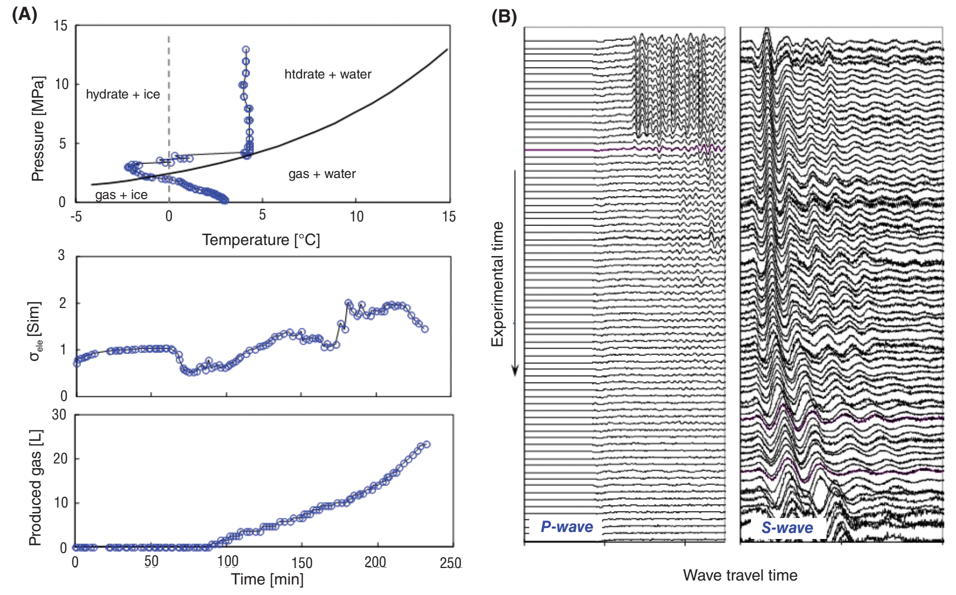

Figure 5. Monitored gas production tests using IPTC: [A] Evolution of pressure, temperature, electrical resistivity, and produced gas (Krishna-Godavari Basin; Yun et al., 2010); [B] Typical wave signatures during gas production: P-wave signatures eventually fade out after gas production; S-waves detect the evolution of the skeleton shear stiffness during hydrate dissociation and gas production (Ulleung Basin; Yun et al., 2011).

Sensors. Transducers are mounted at the tip of tool rods and wired through the central bore. Available instruments are shown in Figure 4. Small-strain wave velocity measurements employ bender elements for S-waves and pinducers for P-waves (Fig. 4a and 4b; peripheral electronics and test procedures as described in Lee and Santamarina, 2005a, 2005b).

While large-strain strength data can be gathered using the DSC (Fig. 2c), we have developed a strength-penetration probe as well (Fig. 4c). This device determines the sediment strength using a cone-shaped stud equipped with a full-bridge strain gauge inside. The measured tip resistance during probe penetration reflects the sediment undrained shear strength (Yun et al., 2006).

Fluid conductivity can be determined using the flexible wall system built within the ESC (Figs. 2b), and can be inferred using the fluid sampling tool (Fig. 4d). This is a self-drilling drainage port with a pressure or volume control to drive the interstitial fluids out of hydrate-bearing sediment. The pressure difference can be selected to preserve hydrates within stability conditions.

Electrical resistivity is measured using an electrical needle probe that is gradually inserted into the specimen to determine a radial resistivity profile with millimeter-scale spatial resolution (Fig. 4e; details and measurement procedure in Cho et al., 2004). We have also developed a multiple electrode system at the base of the effective stress cell that allows us to conduct a surface-based electrical resistivity tomography within a specimen.

The thermal probe consists of a thermocouple deployed at the tip of a tool rod. When pushed into the sediment, the thermal probe monitors the temperature inside the core (Fig. 4f). Internal temperature measurements can be used to monitor phase transitions during controlled gas production studies and to determine thermal conductivity. In addition, the transient plane source (TPS) sensor for thermal conductivity measurements—developed at the U.S. Department of Energy National Energy Technology Laboratory (Fig. 4g; Rosenbaum et al., 2007)—can be installed on the tools or on the pedestal of the ESC and DSC.

Monitoring Dissociation – Gas Production

All PCCT chambers allow core-scale gas production tests by depressurization, heating, or chemical injection (e.g., inhibitors or carbon dioxide). Monitoring data include pressure, temperature, produced gas and water, stiffness (seismic wave velocities), fluid conductivity, and electrical resistivity. Figure 5 shows examples of data gathered during the depressurization of natural hydrate-bearing sediments.

Conclusions

Pressure core technology is needed for the proper evaluation of natural hydrate bearing sediments. The set of pressure core characterization tools (PCCTs) described in this review allow the manipulation, sub-sampling, and extensive assessment of natural gas hydrate bearing sediments under *in situ* pressure, temperature, and effective stress conditions.

In addition to pressure core testing, comprehensive characterization programs should include sediment index properties analyzed within the framework of available data for natural hydrate bearing sediments, and tests with remolded specimens with synthetic hydrate. Pressure core technology can also be deployed to study other gas rich hydrocarbon formations such as deep-sea sediments, coal bed methane, and gas shales.

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Scientific Drilling in the East African Rift Lakes: A Strategic Planning Workshop

by James M. Russell, Andrew S. Cohen, Thomas C. Johnson, and Christopher A. Scholz

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Introduction and Key Science Themes

The East African Rift lakes offer unparalleled opportunities to investigate fundamental climate, environmental, biological, and geological processes through deep coring into the lake bed. Their sediments hold signals of the evolution of tropical rainfall, temperatures, and winds across 20° of latitude on both sides of the equator from the Miocene to the present. Fossil material in these basins chronicles the development of the East African landscapes in which our own species evolved, and records the explosive evolutionary radiation of literally thousands of species of fish, snails, and other aquatic organisms endemic to East Africa's lakes. Drilling these sediments will also provide insights into the tectonic processes that shape the largest active continental rift system on Earth today.

The past decade has witnessed major advances in our efforts to obtain long climate records from the East African lakes, highlighted by the successful scientific drilling of Lake Malawi in 2005 (Scholz et al., 2007). Since 2005, newly acquired and ongoing geophysical surveys by industrial and academic scientists have provided us with much of the requisite site survey information to propose scientific drilling projects in some of the premier target lakes in East Africa, most notably Lake Turkana, Lake Albert, and Lake Tanganyika (Fig. 1). To strategically plan for the next decade of scientific drilling in East Africa's lakes, the U.S. National Science Foundation (NSF) and Past Global Changes (PAGES) project sponsored "Continental Drilling in the East African Rift Lakes", a workshop attended by thirty-six African, European, and U.S. scientists and hosted by Brown University in Providence, Rhode Island, U.S.A. on 14–16 November 2011.

Recent years have witnessed significant developments in multidisciplinary sciences in the African rift. There are ongoing initiatives to integrate paleoenvironmental and paleoanthropological data to understand the environmental context of hominid evolution. These include the International Continental Scientific Drilling Program (ICDP)- and NSF-sponsored Hominid Sites and Paleolakes Drilling Project (HSPDP, http://www.icdp-online.org/front_content.php?idcat=1225); new initiatives to investigate the fundamental processes underpinning rift initiation and evolution (e.g., GeoPRISMS, http://www.geoprisms.org/); and new observational and climate modeling efforts to understand East African climate history. Workshop participants reviewed past studies and current initiatives to define scientific goals and priorities in the critical areas of East African paleoclimate, rifting processes, and ecosystem evolution. We then reviewed the stratigraphic architecture and environmental history of Lake Turkana, Lake Albert, and Lake Tanganyika to evaluate their potential for addressing key scientific questions in order to develop a strategic plan for drilling projects in the East African lakes.

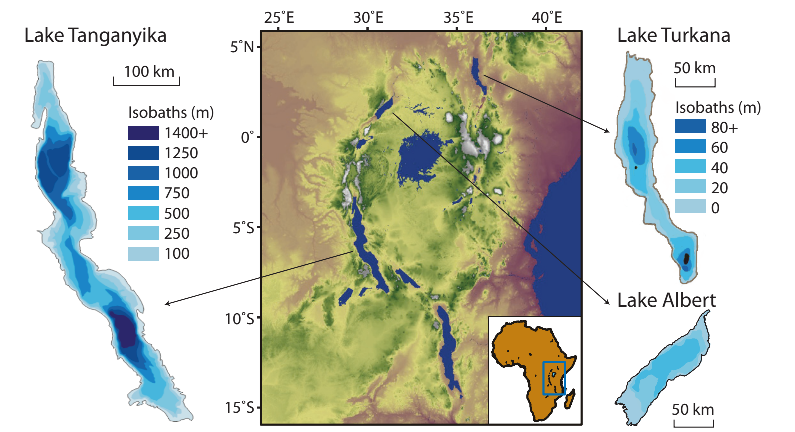

Figure 1. Elevation map of East Africa with bathymetries of Lake Tanganyika, Lake Turkana, and Lake Albert. The inset in the central figure shows the general location of the East African Rift (blue box). Isobaths for Albert and Turkana follow the same color scheme (right).

Plio-Pleistocene East African Climate

Decades of research have provided us with a relatively coherent picture of climate change at the high latitudes during late Cenozoic time, including iconic marine sedimentary records and ice cores that document glacial-interglacial variability and abrupt, millennial climate change (Fig. 2). Unfortunately, our understanding of tropical climate systems, and particularly continental tropical climate, lags far behind our knowledge of the high latitudes. Only recently we thought that African climate marched largely to the beat of the northern high-latitude ice sheets, yet drill cores recovered by the Lake Malawi drilling project revealed the existence of major droughts in Southeast Africa, far exceeding the aridity experienced during the Last Glacial Maximum, prior to 75,000 years ago (Scholz et al., 2007). These droughts appear to have been forced by eccentricity modulation of orbital precession, and they possibly affected the dispersal of anatomically modern humans both within and out of Africa (Blome et al., 2012). Still, the Malawi drill cores cover only the latter part of the Pleistocene and record climate history at the southernmost end of the African rift—a climate setting that differs considerably from the rest of the rift to the north. Recent modeling studies have suggested strong linkages between Plio-Pleistocene changes in the sea-surface temperature structure of the tropical Pacific and Indian Oceans and changes in East African rainfall (Brierley and Fedorov, 2010), potentially affecting the evolution of our species. These new perspectives call into question many of the fundamental mechanisms and processes causing African climate variability, including the following. Are megadroughts present at sites to the north, and are they antiphased in their timing relative to those in Malawi as predicted by the precessional insolation forcing model? How consistent is the relationship between precessional orbital forcing and East African climate through the Plio-Pleistocene?

Numerous outcrop and marine sediment records from tropical East Africa suggest that East African climate has responded to a complex and interrelated set of climate forcings. These include orbitally-driven changes in insolation, changes in global ice volume and atmospheric greenhouse gas concentrations, long-term reorganizations of the principal modes of sea-surface temperature variability such as El Niño–Southern Oscillation (ENSO), and tectonically-driven changes in oceanic and atmospheric circulation (Scholz et al., 2007; Tierney et al., 2008; Brierley and Fedorov, 2010). Understanding the governing mechanisms and sensitivity of African climate to these phenomena will require long and continuous climate records extending into at least the Pliocene to observe East African climate responses across multiple events and time scales. Moreover, the Pliocene offers the most recent extended warm period, when atmospheric greenhouse gases approached values similar to those we will witness in the near future, and when continental configurations were similar to those today (Committee on the Earth System Context for Hominin Evolution, 2010). Workshop participants highlighted that such records will allow us, for the first time, to address various questions:

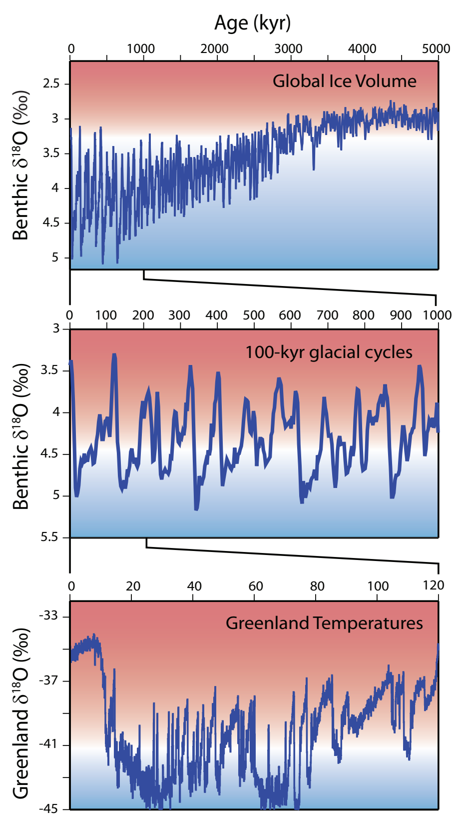

Figure 2. Climate change at different time scales as indicated by marine foraminiferal benthic oxygen isotopic data (Liesecki and Raymo, 2005) and oxygen isotopic reconstructions of Greenland temperatures (Members North Greenland Ice Core Project, 2004).

- What are the dynamics of late Miocene-Pleistocene (last 7 Myr) African climate as a consequence of the mid-Pliocene termination of a permanent El Niño, ocean circulation change with the closure of the Indonesian seaway, the onset, intensification, and changes in the periodicity of Northern Hemisphere Glaciation, and the development of and interactions with East African Rift topography?
- What is the sensitivity and spatial variability of East African hydrology and temperature to orbital-scale climate forcings? Are tropical air temperature and hydrologic change coupled through time, and what are their sensitivities to radiative forcing from greenhouse gases and seasonal insolation?
- How do the rates and amplitudes of East African climate change on millennial to decadal time scales vary as a function of mean climate state? What are the mechanisms underpinning this time scale of variability?

Fundamentally, our goal is to understand the Plio-Pleistocene climate evolution of Africa at a resolution comparable to the records of climate from the high latitudes (Fig. 2), providing key new insights into the dynamics of tropical continental rainfall variability and sensitivity.

Rift Initiation and Evolution

The general notion is that the East African Rift formed as heat flow from the convecting mantle weakened the lithosphere and allowed the African Plate to stretch and fracture along pre-existing weaknesses in the lithosphere (Ebinger, 1989). This, coupled with the introduction of magma in at least some parts of the rift, led to rapid deformation and localization of strain along pre-existing lithospheric structures. However, these simple conceptual models fail to explain the rates and complexity of rifting processes, and the relative roles of magmatism, volatiles, and pre-existing structures in the rifting process are very poorly known. Both magmatism and reactivation of pre-existing structures can help to explain rift initiation and lithospheric stretching (Dunbar and Sawyer, 1989; Buck, 2004), given the relatively weak forces involved in extensional plate tectonics, whereas volatiles such as H_2O and CO_2 can further accelerate fault movement through their effects on the melting point of mantle solids,pore pressures, and metasomatism (Floyd et al., 2001). Magmatism and volatile content also likely play a key role in regulating the movement of faults and associated long-term fault slip rates. Investigation of the volatile contents in drill core pore waters, downhole heat gradients, tephrastratigraphy, and the frequency of seismically-triggered sedimentary events could all shed light on these issues.

We have a limited understanding of the intertwined processes of rift tectonics, magmatism, erosion, and sedimentation and their evolution in space and time, as in today's rift basins we thus far see only the end products of processes integrated over millions of years. For instance, the evolution of elevated rift flanks has a large impact on regional rainfall and erosion and interacts with the large-scale monsoon circulation over East Africa. Eroded sediment, in turn, may substantially impact the rifting processes and architecture (Spiegel et al., 2007). Addressing these issues will require detailed, multidisciplinary analyses of rift basins and their sediments, and they reflect key initiatives within the GeoPRISMS program (Morgan et al., 2011).

In particular, drill cores could help to evaluate the following three important factors:

- the rates of border fault slip in the rift basins, and how they are constrained by geothermal gradients and volatile concentrations;
- the relationships between long-term fault slip rates and short-term seismic hazards such as earthquake recurrence; and
- long-term erosion rates, sediment budgets and accumulation, and their temporal variability to help to constrain rates of crustal cycling.

Addressing these issues will require investigation of rift evolution in space and time, coupling drill core analyses with detailed seismic stratigraphic surveys, thermochronologic studies of landscape evolution, and studies of erosion and deposition in present-day lakes.

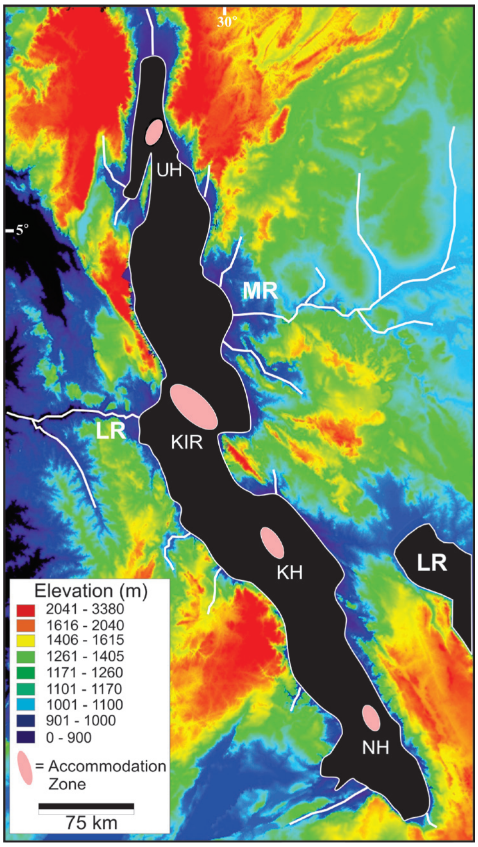

Figure 3. Digital elevation model of the Tanganyika basin showing the location of submerged high-relief accommodation zones within the lake. UH=Ubwari horst, KIR=Kavala Island Ridge, KH=Kalya horst, and NH=Nitiri High. At left, LR=Lukuga River, Tanganyika's outlet. At right, LR=Lake Rukwa, and MR=Malagarasi River. Modified from McGlue et al. (2008).

Human, Floral, and Faunal Evolution

The East African Rift lakes harbor some of the best examples of explosive speciation on the planet (Martens, 1997). Best-known are East Africa's cichlid fishes, which have evolved into groups of literally hundreds of endemic fishes in Lake Tanganyika, Lake Malawi, and Lake Victoria; however, these lakes also contain highly diverse endemic groups of snails, diatoms, ostracodes, and crabs. Tools of molecular genetics now allow for analysis of DNA preserved in fossils of many of these groups, potentially allowing the reconstruction of the genetic history of entire species, from evolution to (in some cases) extinction. Moreover, the East African Rift houses the fossil record of our own lineage and contains some of the most extensive dryland biomes on Earth. Nowhere else can lacustrine scientific drilling provide such fundamentally important insight into the coupling between environmental change and biological evolution (Martens, 1997), including the evolution of *Homo sapiens* (Commiittee on the Earth System Context for Hominin Evolution, 2010).

Lake drill cores can provide more than simply the climate and environmental background in which new species evolve. The rich fossil records preserved in many rift basins could be used to address the rates of change, linearity, and sensitivity of the evolution of species as well as ecosystems and ecosystem processes. Such work would involve a nested approach to identify time scale dependence of ecological and evolutionary responses.

Drilling of extant lakes such as Tanganyika, Turkana, and Albert would dovetail extremely well with the HSPDP, which will provide new drill core from multiple paleolake basins in East Africa, each spanning several hundred thousand years to target key intervals of hominin evolution. These new cores will provide valuable records of environmental variation at hominin sites with direct links to fossil-bearing outcrops; however, these records will be spatially and temporally discontinuous. Long and relatively continuous lacustrine sedimentary records spanning the Plio-Pleistocene, such as what we could obtain from Africa's extant great lakes, would provide a climatic framework in which to interpret the shorter HSPDP records. While marine sedimentary records could further augment this broader context, ongoing piracy in the western Indian Ocean unfortunately constrains marine coring in this region. Drill core from Lake Tanganyika, Lake Turkana, and/or Lake Albert could thus prove instrumental to studies of the climatic context of hominin evolution (Committee on the Earth System Context for Hominin Evolution, 2010).

Study Sites and Target Selection

Sedimentary records exist in Lake Tanganyika, Lake Turkana, and Lake Albert to answer these questions, but each lake affords very different temporal windows on past climate, different styles of rifting, and different opportunities for understanding evolutionary biology. Moreover, each lake offers very different opportunities in terms of their time scale, resolution, and continuity.

Lake Tanganyika

Tanganyika (32,600 km^2, 1471 m deep) is the largest, oldest, and deepest lake in East Africa, with an estimated age of 9–12 Ma (Cohen et al., 1993). Tanganyika is one of the most biodiverse lakes on Earth, hosting endemic cichlid fish, snails, ostracods, crabs, and other organisms, and it lies within the vast but poorly understood Miombo woodland ecosystem of SE tropical Africa. Tanganyika is comprised of four major sub-basins separated by deep-water horsts and provides very clear examples of rift segmentation, fault behavior, and structural growth that could greatly facilitate studies of fault behavior and seismicity. Although the Rungwe volcanic field to the south provides occasional tephras to Tanganyika, there is no extensive volcanism in the basin.

Tanganyika lies within the core path of the Intertropical Convergence Zone's migration over central Africa. Its late Quaternary climate history is largely out of phase with Lake Malawi, indicating that Tanganyika acts as a Northern Hemisphere site despite its location. Drill core data from Tanganyika will therefore complement, not replicate, studies in Lake Malawi. The proximity of both Tanganyika and Malawi to the Rungwe Volcano could facilitate inter-basin tephrstratigraphic studies. Moreover, recent work has demonstrated Tanganyika's potential to record climate processes at orbital, millennial, and even interannual time scales, as the sediments contain a wealth of climate proxies preserved in often laminated sediments (Cohen et al., 2006; Tierney et al., 2008, 2010). Most importantly, recent work has documented deep-water horst blocks (Fig. 3) with condensed sedimentary sequences (Fig. 4), putting early Pliocene-age sediment within relatively easily drilling depths at sites (McGlue et al., 2008). These sites are located at high-relief accommodation zones in deep enough water to have continuous deposition over much, if not the entirety, of this time. The Kalya and Nitiri horsts in Tanganyika's southern basin, in particular, lie in deep water below the depth of maximum lake lowstands and appear to house long and continuous sedimentary sections (McGlue et al., 2008; Fig. 4).

While the challenges and cost of drilling a long hole in deep water (500 m of mud in 700 m of water, for instance) are considerable, the group felt that drilling Tanganyika presented the most exciting scientific opportunities of any African lake. Tanganyika's deep-water horsts are perhaps the only depositional setting in East Africa likely to contain continuous Pliocene-present sediments at easy drilling depth. The potential significance of a continuous, high-resolution, Pliocene-present sediment record for tropical paleoclimatology, paleoanthropology, evolutionary biology, and rifting processes far outweighs the significant time and investment required to move the Tanganyika record forward.

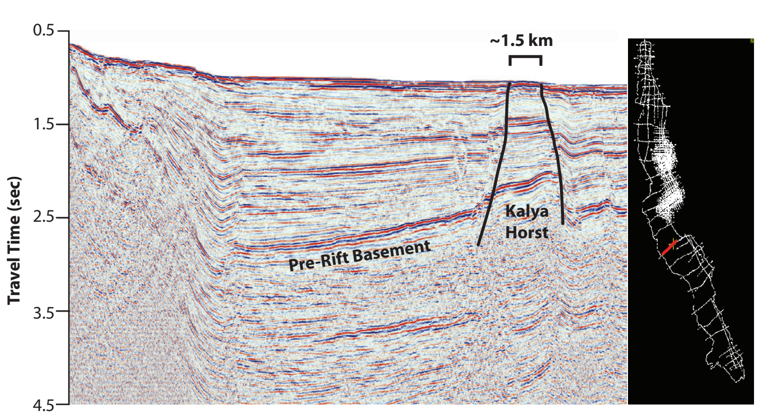

Figure 4. Seismic section from the northern end of the Kalya horst; location of the seismic section within Lake Tanganyika is illustrated by the red line within the seismic grid at right. Note the presence of a continuous and condensed sedimentary sequence above pre-rift basement on the Kalya horst, indicated by the bracket. Data are from Project PROBE (Rosendahl, 1988).

Lake Turkana

Rifting and volcanism have affected the Turkana basin since the Oligocene, with the modern lake developing in the Pliocene. Turkana is well-known for its complex rifting history, and it has extensive and remarkable facies architecture (clastic/carbonate sequences) that house world-famous vertebrate and hominin fossil locales. However, the rifting processes in Turkana are the most complex of the three lakes, and there are extensive and relatively young basalts that may resurface parts of the Turkana basin. The modern aquatic biota is relatively depauperate, but drilling in Turkana could dovetail with planned drilling of early Pleistocene lake beds in west Turkana as part of HSPDP and provide the most direct linkage to paleoanthropology of the three lakes.

Lake Turkana is East Africa's northernmost rift lake, and its sediments could provide important insight into the climate of northeastern Africa that would strongly complement recent drilling efforts on Lake Malawi. Turkana is extremely sensitive to climate variability, and this is reflected in the lake's sedimentary record (Halfman et al., 1994). Moreover, there is a well-established tephrastratigraphy for Turkana that would aid in developing age models for drill cores. However, the modern lake is characterized by very high sedimentation rates, and the lake is certain to have undergone desiccation events that were likely associated with basin deflation. Moreover, on long time scales the complex paleogeography and rift history could complicate paleoclimate reconstruction. To further complicate matters, available seismic reflection data from Turkana are rather poor, requiring significant efforts to properly locate drilling targets. Some aspects of drilling logistics in Turkana are relatively simple, but the remote location, high winds, and lack of facilities will make Turkana a logistically challenging target.

In sum, Turkana presents many exciting and extremely valuable opportunities, particularly the development of a high-resolution climate record spanning the late Pleistocene at the northern end of the East African Rift and in a site of paleoanthropologic importance. Yet, the complications posed by high sedimentation rates, hiatuses, and a complex rifting history make Turkana a lower priority than Tanganyika.

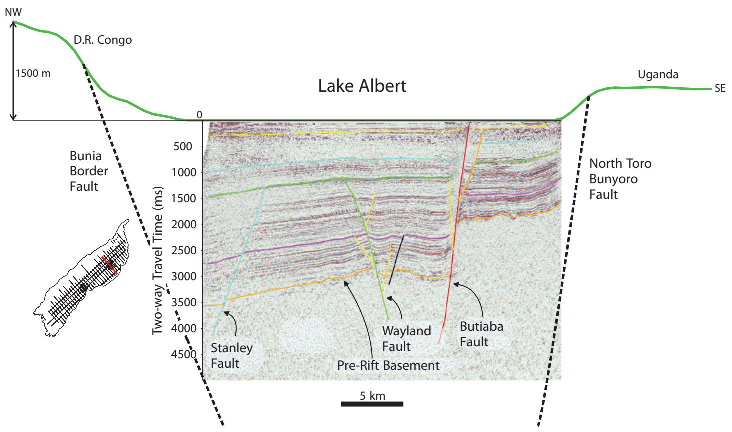

Figure 5. Seismic section from Lake Albert, modified from Karp et al. (2012). The thick green line at top traces the height of the landscape above Lake Albert. Colored lines in the seismic section indicate boundaries between sedimentary units as well as major faults. The location of this section is indicated by the red line within the map of the seismic grid at left. Note the condensed sedimentary section on the southeast side of the basin.

Lake Albert

Lake Albert is situated near the equator in the western arm of the East African Rift. The basin contains, in places, several kilometers of lacustrine and fluviolacustrine sediments that extend into the Miocene (Fig. 5), with considerable outcrop exposures that have been investigated for their fossil content and paleobiology. Drilling in Lake Albert could elucidate how rift-generated topography and the uplift of the Rwenzori Mountains control sedimentation and rift catchments, and it could further elucidate the history of the source of the White Nile River. Moreover, the Albertine Rift is in many ways simpler than Tanganyika and Turkana, facilitating studies of rifting processes. Drilling in Lake Albert could provide incredibly valuable new records of the late Miocene to present evolution of East African climate. However, discontinuities existing even in late glacial sediments indicate the likelihood of numerous hiatuses in longer drill core records when climate fluctuation may be more extreme.

Perhaps the strongest argument for drilling Albert lies in the extensive infrastructure related to recent oil discoveries in the Albert basin by Tullow Oil, plc (http://www.tullowoil.com). There is an exquisite seismic-stratigraphic framework for Lake Albert, and drilling infrastructure is already available in the basin. Lake Albert is the main depositional sump for much of central equatorial Africa, including Lake Victoria and Lake Edward, and could therefore provide an unparalleled but discontinuous record. Given the likelihood of discontinuities in drill core data, Lake Albert was prioritized beneath Tanganyika, but given Albert's extraordinary record and the near certainty of future industrial drilling activities, the group felt that we should work to partner with industry in drilling activities, perhaps through onshore drilling where condensed sections are present (Fig. 5).

Summary and Future Work

Scientific drilling in Lake Tanganyika, Lake Turkana, and Lake Albert can answer fundamentally important questions concerning tropical climate variability and change, rifting processes, paleobiology, and human evolution. Among these lakes, Tanganyika stands out as an extraordinary opportunity due to the presence of continuous, deep-water sedimentary records spanning the Pliocene to present, as well as being the nexus of interest in the lake basin for paleoclimatologists, seismologists, and evolutionary biologists. Workshop participants were uniquely enthusiastic about moving forward, and they agreed on several benchmarks to begin a continental drilling project on that lake.

First, and most importantly, existing seismic reflection data from Tanganyika is of very high quality but low spatial resolution. Beach Energy (Adelaide, South Australia) will acquire new deep seismic reflection data from Tanganyika's southern basin, which contains the best drilling targets on deep-water horst environments, and the company could make sections of this data available. These data will provide an excellent seismic-stratigraphic framework for interpreting drill core records but is unlikely to have the resolution needed to detect small-scale unconformities and site drilling sites. The group agreed that our first step should be a proposal to acquire high-resolution data and shallow piston cores over deep-water horsts in Tanganyika's southern basin to determine appropriate drilling targets and identify major sedimentary facies likely to be encountered in scientific drilling.

Secondly, the group expressed interest in accessing extensive existing shallow core collections from Tanganyika, metadata on which is not widely accessible. The group agreed that we would make information about these cores accessible through LacCore (http://lrc.geo.umn.edu), University of Minnesota, to allow for sample analysis, testing, and proxy calibration and to expand the science team involved in Tanganyika drilling.

Finally, there were several more specific studies that could complement a Tanganyika drilling project, ranging from tephrastratigraphic studies of the Rungwe volcanics to limnological studies in the Tanganyika basin. The group agreed to pursue these through PI-driven proposals to relevant science agencies, with coordination and data sharing to build the Tanganyika drilling program.

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Unlocking the Opening Processes of the South China Sea

by Chun-Feng Li, Pinxian Wang, Dieter Franke, Jian Lin, and Jun Tian

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Introduction

The South China Sea (SCS) is a classical representative of western Pacific marginal seas (Figs. 1, 2). It developed from continental margin rifting, and its central portion is floored with oceanic crust. Despite its relatively short evolutionary history, compelling research opportunities abound for a multitude of key tectonic processes ranging from rifting through seafloor spreading to subduction, as well as for the cyclical climatic changes with broad regional impact. Its relatively small size and young age compared to major ocean basins facilitate tectonic comparisons between conjugate continental margins and make the entire basin accessible through a single expedition of scientific ocean drilling. These attributes make the SCS an exemplary natural laboratory for studying continental break-up, sedimentary basin formation, mantle and lithosphere evolution, and land-ocean interactions. However, lack of any deep scientific borehole in the central SCS basin leaves a gap in understanding of the opening mechanisms, timing of the onset and termination of seafloor spreading, and environmental history in the region.

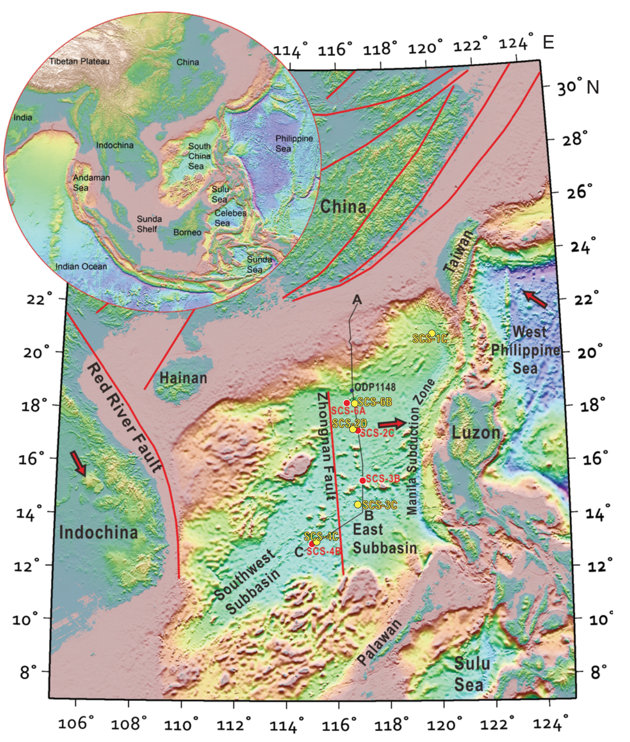

Figure 1. Regional topography and tectonic framework of Southeast Asia (from Shi and Li, 2012). Data based on Smith and Sandwell (1997). Red lines mark major faults. Red and yellow solid points are locations of the proposed drilling sites (red-primary sites; yellow-alternate sites). The black lines labeled with AB and BC are seismic sections shown in Fig. 3. Red arrows indicate the direction of plate movement.

To advance research of Southeast Asia and the SCS through scientific ocean drilling, an international workshop entitled “Unlocking the Opening Processes of the South China Sea” was held on 31 January–1 February 2012 in Shanghai, China. It was the first international workshop devoted to scientific ocean drilling in the SCS in the recent decade. Building on an existing Integrated Ocean Drilling Program (IODP) drilling proposal (Li et al., 2012), this workshop sought contributions from the broad international community, including scientists from non-IODP member states that have a strong scientific interest in the SCS. The overarching goal of the workshop was to develop the most efficient research and drilling strategy to address key questions in tectonics and environmental history of the SCS within a single, initial IODP expedition.

The workshop hosted sixty-five participants from fifteen countries and regions, including scientists from several non-IODP member states surrounding the SCS (Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam). The workshop was jointly sponsored by the IODP-MI, IODP-China, the South China Sea Deep (SCSD) Program of the National Natural Science Foundation of China (NSF-C), and the State Key Laboratory of Marine Geology at Tongji University, China. The lead conveners were Pinxian Wang and Chun-Feng Li of Tongji University, and Dieter Franke of the Federal Institute for Geosciences and Natural Resources, Germany.

The workshop was charged with the following three tasks.

1. To identify key scientific questions on tectonics and environmental history of a marginal sea that can be addressed through scientific drilling in the SCS, and to develop an efficient research and drilling strategy to address these questions
2. To recommend ways to improve the IODP Proposal 735-CPP through focusing drilling objectives, refining drilling targets, and augmenting site survey data
3. To foster cooperation in research of the Southeast Asia region through engagement of a broad international scientific community including scientists

from non-IODP member states surrounding the SCS

Scientific Background

With its area of 3.5 million km^2 and maximal depth of 5500 m, the SCS is one of the largest marginal seas in the world (Figs. 1, 2). Since the Late Mesozoic, it has been at the center stage of many first-order tectonic and paleoclimatic events. Mesozoic subduction of the paleo-Pacific plate, a fragment of which developed roughly along the present-day northern SCS continental margin (Taylor and Hayes, 1983), gradually dispelled Paleo-Tethys and built a massive orogen in Southeast Asia. However, during the transition from the Early to Late Cretaceous, all supportive evidence of the subduction zone disappeared, while regional extension started to prevail (Shi and Li, 2012). This was followed by the Cenozoic opening of the SCS, via continental break-up and subsequently seafloor spreading. The early work of Taylor and Hayes (1980, 1983) and Briais et al. (1993) suggested that the SCS opened from ~32 Ma to ~16 Ma during the Oligocene and Early Miocene. Presently located between the Earth's largest ocean and the largest continent and being near the Pacific Warm Pool, the SCS also plays a significant role in affecting the global climate system (Wang and Li, 2009).

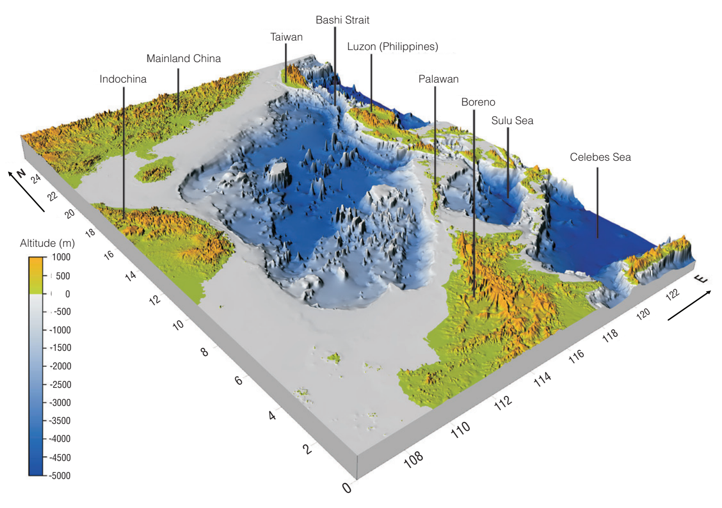

Figure 2. A 3D view of the Southeast Asia topography and South China Sea bathymetry (from Wang and Li, 2009).

The SCS is uniquely situated for studying continental break-up, basin formation, and seafloor spreading processes for several reasons.

1. It is a classical representative of western Pacific marginal seas that developed from continental break-up and has evolved into seafloor spreading.
2. The SCS is located at the junction of the Eurasian, Pacific, and Indo-Australian plates and therefore is sensitive to tectonic and climatic changes associated with the surrounding plates.
3. Its relatively small size and young age facilitates easy tectonic comparisons between the two conjugate continental margins.
4. Despite its short evolutionary history, the SCS has undergone a complete Wilson cycle from continental break-up and seafloor spreading to subduction. Therefore, it is well suited for studying various plate boundary activities, such as oceanic subduction (e.g., the Manila Trench), strike-slip faulting (e.g., the Red River Fault), and active orogenic processes (e.g., Taiwan).
5. The rifting style of the SCS margins may represent an intermediary form of continental extension between the end-member scenarios of highly magma-rich (e.g., North Atlantic margins) and magma-poor or hyperextended (e.g., Iberia and Newfoundland) margins.
6. The SCS is associated with high sedimentation rates and carbonate preservation, providing complementary records to those from the poorly preserved carbonates in the western Pacific Ocean.

All these attributes make the SCS an ideal natural laboratory for studying continental break-up, basin formation, deep mantle evolution, and land-ocean interactions. However, there is not yet one single deep drilling well in the central SCS basin targeting the oceanic crust or its transition from the continental crust. This leaves a large gap in understanding the opening mechanisms and timing of the onset and termination of seafloor spreading in the SCS.

In 1999, ODP conducted the first deep scientific drilling, Leg 184, in the SCS, focusing primarily on Asian monsoon and environmental history of the region (Wang et al., 2000). Leg 184 cored seventeen holes at Sites 1143–1148 in the SCS and recovered 5463 meters of sediment. The suite of sites yields an almost continuous record of the environmental history of the SCS during the last 32 Ma. Leg 184, however, was neither sited for recovering pre-rift and syn-rift strata, nor did it reach the oceanic crust basement. This leaves the SCS basin completely unconstrained in terms of its formation history.

Scientific Debates on the Tectonics of the SCS

Among the continents of the world, Asia has been subjected to the most significant Cenozoic deformation. Coincident with the large-scale deformation of Asia, many of the marginal seas in the western Pacific stopped spreading during the early Miocene. However, the opening mechanisms and driving forces for the SCS basin are still debated. One model links the opening of the SCS basin with the Red River fault zone, which has at least 500–600 km of left-lateral displacement created during the Oligocene and Miocene

(Tapponnier et al., 1982; Briais et al., 1993). Alternative models relate the opening of the SCS to subduction under Borneo (Taylor and Hayes, 1980, 1983; Holloway, 1982; Hall, 1996) and the influence of subduction beneath the Philippines, driving a back-arc type of extension in the overriding plate (Taylor and Hayes, 1980).

Another major topic of debate is the timing of the onset and termination of seafloor spreading in the SCS. Largely based on interpretation of magnetic anomalies, estimations of the oceanic crust age for the east sub-basin were 32–17 Ma (Taylor and Hayes, 1980, 1983), 32–16 Ma (Briais et al., 1993; Li and Song, 2012), and 31–20.5 Ma (Barkhausen and Roeser, 2004). For the southwest sub-basin, the estimations of the oceanic crust age differ widely from 27–16 Ma (Briais et al., 1993; Li and Song, 2012), to 25–20.5 Ma (Barkhausen and Roeser, 2004), and to 42–35 Ma (Yao et al., 1994). Furthermore, Hsu et al. (2004) proposed the existence of oceanic crust as old as 37 Ma on the northeast part of the SCS. Such large discrepancies in the proposed magnetic ages of the oceanic crust point to the critical importance of direct sampling and dating the oceanic basement rocks through deep drilling in the SCS.

Workshop Deliberation

The two-day workshop consisted of a mix of presentations, breakout sessions, and plenary discussion. The meeting featured five keynote addresses, thirty oral presentations, and twenty-five posters. These presentations covered a wide range of topics pertinent to tectonics and environmental history of Southeast Asia and the SCS. While the majority of presentations focused on the tectonic and magmatic evolution of the region and comparisons with other examples of continental rifting, basin formation, and seafloor spreading, participants also showcased work on paleoceanography, sedimentology, and biogeochemistry of the region. In addition, the meeting featured a presentation on the IODP proposal process, commentary on the current IODP drilling engineering capability, and a review of the previous panel comments and recommendations on the IODP Proposal 735-CPP.

The workshop devoted a significant amount of time to breakout sessions and plenary discussion. The breakout subgroups were charged with developing recommendations along four thematic lines.

1. What are the "big picture" science questions that are of global significance and can be addressed through scientific drilling in the SCS?
2. How can the drilling objectives, targets, and strategy of the IODP Proposal 735-CPP be prioritized? How can the site survey data be improved?
3. What are other future potential drilling objectives and targets in the SCS?
4. How can we strengthen future international cooperation in research of Southeast Asia and the SCS?

The workshop participants were divided into four subgroups, each of 15–18 members with mixed expertise. Key findings from the four subgroups were remarkably consistent, pointing to a prioritized strategy of scientific drilling in the SCS.

Workshop Recommendations

Through ample discussion at both plenary discussion and breakout sessions, the workshop reached a consensus on a prioritized ocean drilling strategy in the SCS with the following key recommendations.

(1) The initial top drilling priority is to constrain the timing of the start and end of seafloor spreading events in the SCS.

This objective can be achieved through a single expedition drilling into oceanic basement rocks in both the east and southwest sub-basins. It was felt that sampling and dating oceanic basement rocks through deep drilling is the only way to ground truth the hypothesized oceanic crust age, based on interpretation of magnetic anomalies.

(2) Transect drilling from the oldest visible seafloor-spreading magnetic anomaly to the extinct spreading axis of the SCS.

All four subgroups suggested that transect drilling should be conducted on both the east and southwest sub-basins.

(3) The sedimentary sequences obtained while drilling into the oceanic basement should be effectively used for studying environmental history of the region.

The above recommendations (1) to (3) were later incorporated in the revised IODP Proposal 735-CPP-2 that was submitted to IODP in April 2012.

(4) The workshop recommended a phased drilling strategy, starting with a leg of drilling the oceanic crust (i.e., IODP Proposal 735-CPP-2) to be followed by future drilling of syn-rifting sequences and Mesozoic strata on both margins of the SCS.

The participants expressed strong interest in drilling syn-rifting sequences on conjugate margins of the SCS. Drilling targets should enable detailed comparison of extension histories on conjugate sides, aiming to document the full extension history of both margins.

Drilling into Mesozoic sediments also has its merits through providing constraints on the critical period before the SCS formation. Drilling the Mesozoic strata could help to test key questions regarding the connection of the Tethys to paleo-Pacific Ocean. Furthermore, evidence from Mesozoic strata could help to test tectonic models and to explore if there is evidence for pre-SCS extension in the Mesozoic.

(5) The participants expressed interest in drilling targets associated with submarine hydrology and deep biosphere of the SCS.

It was felt that hydrology and deep biosphere are important objectives for future drilling in the SCS, but at present information is insufficient to define exact targets. Thus, it would be useful to combine biosphere and microbiological targets with other drilling sites.

Installation of a circulation obviation retrofit kit (CORK) was proposed to study the hydrology, deep biosphere, and carbon cycle. However, it was recognized that the installation of CORK observatories would require intensive effort, and thus careful planning of drilling objectives, sites, and strategy needs to be developed.

Overall, the workshop developed a strong sense of enthusiasm, both from participating scientists and institutions. Participants expressed confidence that if the first phase of drilling (IODP Proposal 735-CPP-2) is approved, subsequent proposals focused on drilling syn-rift sequences and Mesozoic strata and with hydrology/deep biosphere objectives would be developed.

Progress Forward

In April 2012, a revised IODP proposal entitled "Opening of the South China Sea and its implications for Southeast Asian tectonics, climates, and deep mantle processes since the Late Mesozoic" was submitted to IODP. This revised proposal (Li et al., 2012) has incorporated all of the key recommendations of the workshop. Four primary and five alternate drilling sites in the SCS ocean basin were proposed, all aimed at reaching the oceanic basement in order to recover both oceanic basalts and overlying sediments. The revised proposal has adopted the recommended transect drilling strategy with drilling sites in both the east and southwest sub-basins (Figs. 1, 3).

The proposed drilling sites are designed strategically to determine timing of onset and termination of seafloor spreading in different sub-basins, and timing of a possible ridge jump or a volcanic event amid seafloor spreading. These sites will allow geochemical samplings of basement rocks of different ages, yielding critical information on how the crust and mantle have evolved over the time of basin formation. Together the drilling proposal will address research objectives in three major themes: (1) Cenozoic mechanisms, timings, sequences, and affiliations of seafloor spreading; (2) oceanic crustal accretion and mantle evolution; and (3) paleoceanographic and sedimentary responses to tectonic evolution of the SCS.

Links to Other Programs

There are currently several ongoing research programs in the region. One major initiative is the SCSD Program funded by the NSF-C. With a total budget of ~$25M USD, this eight-year research program (2011–2018) aims to reveal the life history of a classical marginal sea through research of the interconnection between tectonic/magmatic, sedimentological, and biochemical processes of the SCS (Wang, 2012). The SCSD Program is currently funding 3D Ocean Bottom Seismometers (OBS) experiments and deep-tow magnetics surveys in the east and southwest sub-basins of the SCS. The program will also sponsor additional site surveys and post-cruise research related to the proposed IODP drilling.

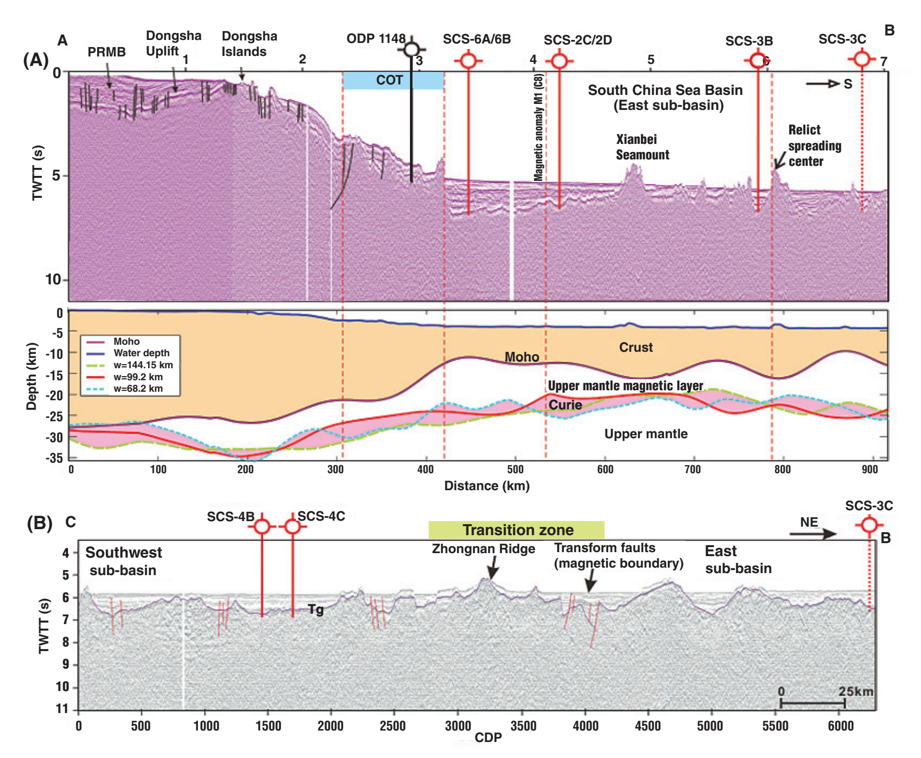

Figure 3. [A] (upper) Proposed sampling transect in the east sub-basin of the SCS (after Li et al., 2010). (lower) The Moho and Curie depths estimated from gravity and magnetic anomalies, respectively. TWTT=two-way travel time. COT=continent-ocean transition zone. PRMB=Pearl River Mouth Basin. w=width of moving windows in estimating Curie depths. [B] Seismic section showing the structures of the southwest sub-basin and the east sub-basin, as well as the transition zone between them. Tg is the Cenozoic basement (after Li et al., 2008).

Following the Shanghai workshop, new site survey data related to the IODP Proposal 735-CPP-2 were provided by several institutions including the China National Offshore Oil Company (CNOOC), Guangzhou Marine Geological Survey (GMGS), National Central University in Taiwan, Federal Institute for Geosciences and Natural Resources (BGR), Germany, as well as by scientists on board a French R/V *Marion Dufresne* cruise in 2012. Acquisition of new site survey data was initiated by the proponents of the IODP Proposal 735-CPP-2 during the summer of 2012.

Acknowledgements

The workshop was jointly sponsored and funded by the IODP-MI, IODP-China, the South China Sea Deep (SCSD) Program of the National Natural Science Foundation of China (NSF-C), and the State Key Laboratory of Marine Geology at Tongji University. We thank all workshop participants and co-proponents of the IODP Proposal 735-CPP-2 for major scientific input and suggestions.

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New Frontiers in Scientific Drilling of the Indian Ocean

by Stephen J. Gallagher, Neville Exon, Dhananjai Pandey, S. Rajan, Mike Coffin, and Ken Takai

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Introduction

The Indian Ocean exerts a fundamental control on the Earth's climate and hosts a variety of complex tectonic features. It influences the Indian Monsoon and hosts a major part of the thermohaline conveyor. It has been over a decade since scientific drilling occurred in the Indian Ocean, and as such there are major gaps in geoscientific understanding of this region. Future drilling of the sedimentary archives in the region will yield substantial information on the history of uplift, erosion, deposition and monsoonal history. It will improve our understanding of greenhouse/icehouse and ocean gateway dynamics and reef development. The region also hosts exceptional examples of Earth system processes and products that drilling will play an important role in illuminating. It would answer questions associated with subduction and tectonic plate breakup and reorganization. Major geodynamic issues to be investigated include hotspot/spreading ridge interactions and constraints on the mantle reference frame. There are many deep biosphere mysteries that may be solved by drilling sediment, such as the impact of Himalayan uplift and the monsoon on subseafloor community diversity. Drilling oceanic crust will reveal the nature of poorly known microbial communities at ridge systems, providing insights into the composition and abundance of microbial communities in different crustal provinces.

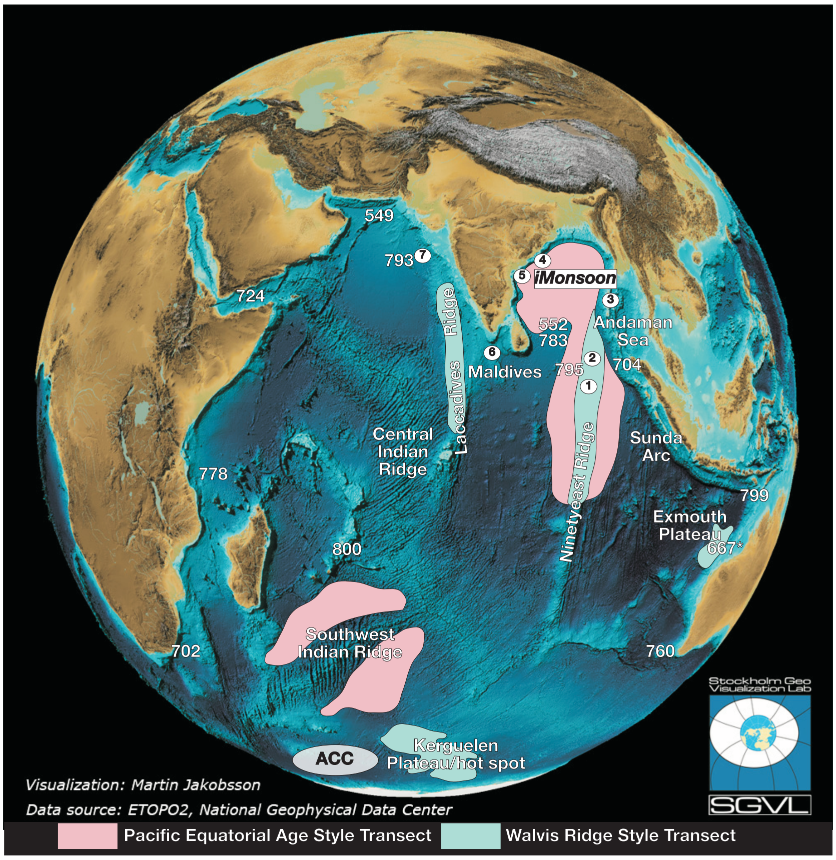

Figure 1. Pre-existing proposals and future drilling prospects in the Indian Ocean. Potential Theme 1 targets include two types of deep ocean transects; ACC=Antarctic Circumpolar Current drifts proposal; Maldives atoll & deep-water proposals. Theme 2 targets include iMonsoon program with locations: 1) DSDP 216, 2) ODP 758, 3) Andaman Sea, 4) Mahanadi Basin, 5) Krishna-Godavari Basin, 6) Cape Cormorin, and 7) Laxmi Basin Kerala-Konkan Basin. Theme 3 targets include most tectonic features shown. Theme 4 could be accommodated in most expeditions. Sourced from: http://www.gebco.net/general_interest/bathymetry_visualisations.html

Workshop Goals

The Indian Ocean IODP Workshop was hosted in Goa in October 2011 by the National Centre for Antarctic and Ocean Research (NCAOR), India. The workshop was initiated and planned by Australian and Indian scientists to improve existing proposals (Table 1), build new proposals, and initiate alliances essential for drilling proposals.

The workshop was attended by seventy Indian and forty international scientists. Participants stressed the importance of the Indian Ocean in the planned new phase of drilling, the International Ocean Discovery Program (IODP, 2013–2023). The aim is to have several new proposals submitted in 2012 for drilling by 2014 or later, centered around global science problems discussed in four themes.

Theme 1: Cenozoic Oceanography, Climate Change, Gateways and Reef Development

Drilling Cenozoic marine sequences will lead to an enhanced understanding of Cretaceous to Paleogene ocean oxygenation; greenhouse to icehouse transitions;

the history of the Indian Ocean Dipole; the Antarctic Circum-Polar (ACC) and Agulhas Currents (AC); the timing of the Indonesian Throughflow (ITF) and the origin of reefs. This theme addresses Challenges 1, 2 and 7 of IODP Science Plan 2013–2023. Three subthemes were discussed.

Table 1. A list of the current active proposals in the Indian Ocean.

Proposal	Short Title	Lead Proponent
549-Full-6	Northern Arabian Sea Monsoon	Lückge, Germany
552-Add	Bengal Fan	France-Lanord, France
595-Full-4	Indus Fan and Murray Ridge	Clift, U.K.
667-Full	NW Australian Shelf Eustasy	Fulthorpe, U.S.A.
702-Full	Southern African Climates	Zahn, Spain
704-Full-2	Sumatra Seismogenic Zone	Goldfinger, U.S.A.
724-Full	Gulf of Aden Faunal Evolution	de Menocal, U.S.A.
760-Pre	SW Australia Margin Cretaceous Climate	Grocke, U.K.
778-Full-2	Tanzania Margin Paleoclimate Transect	Wade, U.K.
783-APL	Indian Monsoon History	Hathorne, U.K.
793-CPP	Arabian Sea Monsoon	Pandey, India
795-Pre	Indian Monsoon Rainfall	Clemens, U.S.A.
799-Pre	West Pacific Warm Pool	Rosenthal, U.S.A.
800-Full	Indian Ridge Moho	Dick, U.S.A.

Evolution of the shallow carbonate environment. Prospective proposals will suggest deep and shallow drill sites in the Maldives Archipelago to better understanding the influence of the monsoon-generated current system and sea-level fluctuations on the Neogene development of the Maldives platform (Betzler et al., 2009). Another potential proposal will address the origin of modern atolls and drowned flat top banks that have developed since the Pliocene.

Deep ocean record of palaeoceanography/climate. A series of transects ("Walvis Ridge Transects", Westerhold et al., 2007; "Pacific Equatorial Age Transects", Lyle et al., 2010; Fig. 1) were suggested to reveal the long-term history of palaeo-CO_2 levels, sea surface temperatures, ocean anoxic events and the Indian Ocean Dipole. Several proposals focusing on recovering deep oceanic and climatic Cretaceous to Neogene records (proposals 760-Pre, 724-Full and 778-Full) have been submitted.

Ocean margin boundary currents and gateways. The ITF and ACC are key drivers of global climate. Understanding the response of these currents to glacio-eustatic and tectonic triggers will allow us to predict their behavior in the future in the context of global climate change. A new version of proposal 667-Full will be submitted in 2012 to investigate ITF and Leeuwin Current history (Gallagher et al., 2009). Another proposal will target ACC history (Barker and Thomas, 2004) by drilling the Conrad Rise. Proposal 702- Full will investigate AC history.

Theme 2: The History of the Monsoons

The Indian monsoonal circulation is the largest atmospheric transport system on Earth, including latent heat (moisture) sources in the southern Indian Ocean, cross-equatorial transport with large-scale convergence and precipitation over the Indian and Southeast Asian regions, and influencing some three billion people seasonally. This circulation system is complex, driven by cross-equatorial pressure gradients dictated by changes in the Siberian High (winter monsoon), Indo-Asian low (summer monsoon) and both summer- and winter-season changes in the Mascarene High of the southern subtropical Indian Ocean. The magnitude and regularity of the cross-equatorial flow make the Indian monsoon unique. Monsoonal circulation is dynamic on various time scales, from weekly to annual to decadal and linked to short time scale ocean-atmosphere interactions, to millions of years associated with regional and large-scale tectonism. Monsoon runoff from the continent has built the two largest fan systems on Earth, the Indus and Bengal Fans. These host a record of potentially high resolution of the history of uplift, erosion, deposition, and carbon burial. An understanding of the mechanisms driving monsoon climate changes at different time scales has high societal importance. Theme 2 addresses Challenges 1, 3–7, 11 and 13 of the IODP Scientific Plan.

Monsoonal Paleoclimate and Paleoceanography (MPP). This focused on the pelagic and hemipelagic archives as recorders of the local and regional responses to monsoon winds and precipitation (Clift and Molnar, 2003). This includes existing proposals 549 Full and 783 APL. The MPP subgroup recommend a workshop to produce a new proposal iMonsoon (Fig. 1) in time for consideration by the program panels and drilling by 2014 or soon after.

Sedimentary source-to-sink studies, using submarine fan (SF) archives. Submarine fans are recorders of long-term changes in erosion, transport and deposition linked to tectonics and climate change principally in the Himalayas (Clift et al., 2008; Gupta et al., 2011). These topics are included in proposals 609-Pre, 552-Full and 552-Add, 595-Full and 776- Full targeting the eastern and western river systems. However, amending these proposals with more proximal sites on each fan would allow the transport history to be better constrained. In this regard, the SF sub-committee also recommended a workshop on geohazards in the northern Bay of Bengal, focusing on the frequency of tropical cyclones, Holocene earthquakes, Pleistocene subsidence, and changing sediment supply due to deforestation and agriculture.

Theme 3: Tectonics and Volcanism

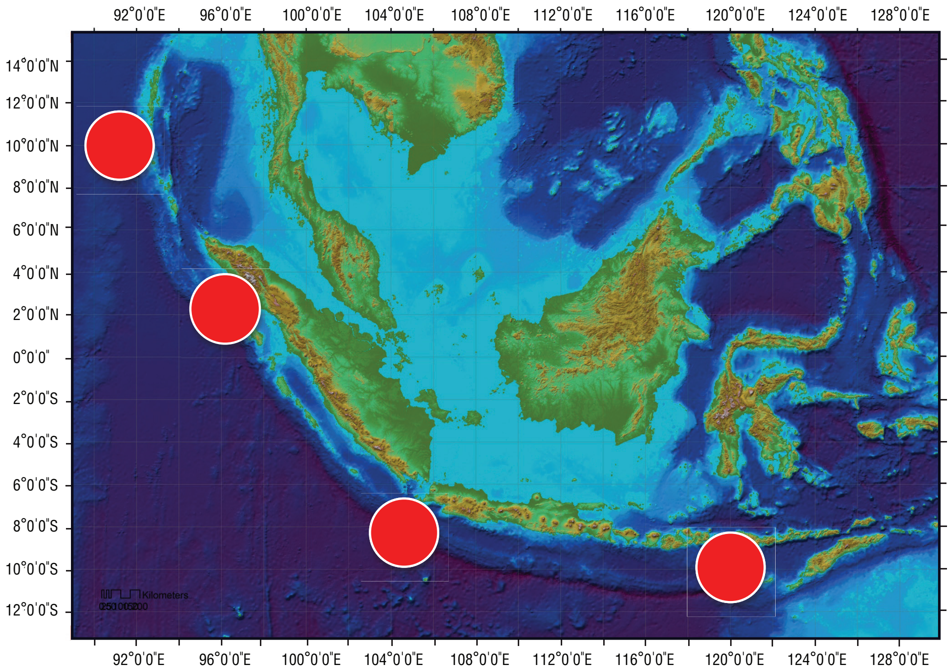

Figure 2. Possible drill sites along the Sunda Arc that represent the transition from collisional tectonics in the east to oblique subduction in the northwest.

The Indian Ocean hosts exceptional examples of Earth system processes and products that ocean drilling will play a key role in illuminating. Tectonic and magmatic objectives address Challenges 12 and 13 of the IODP Science Plan. Tectonic problems include those associated with; 1) subduction—fault properties and slip, sediment effects, role of fluids, segmentation, rupture, tsunamigenesis—along the Sunda arc, site of the great 2004 Indian Ocean earthquake (Gulick et al., 2011) and tsunami (Fig. 2) (proposal 704-Full-2: "Sumatra Seismogenic Zone"); 2) tectonic plate breakup and reorganization associated with Kerguelen and Réunion hotspot activity; 3) India-Madagascar and India Seychelles break-up, origin and evolution of Laxmi and Laccadive ridges and intraplate deformation; and 4) possible incipient plate breakup along the Ninetyeast Ridge. Major geodynamic issues comprise hotspot–spreading ridge interactions and hotspot constraints on the mantle reference frame. Key geochemical questions include those associated with hotspots—Afar, Kerguelen, Réunion—that have sampled nearly the entire scope of mantle source compositions; 1) back-arc spreading magmatism, hydrothermal activity, mineralization, metallogenesis, and biosphere; 2) the testing of existing and development of new models for flood magmatism; 3) the origin and alteration of oceanic core complexes; and 4) the nature of the lower crust and Moho at slower spreading ridges (proposal 800-Full).

Theme 4: The Deep Biosphere

Scientific drilling has revealed the existence of a deep biosphere in surface and deep subsurface sediment and rocks (Roussel et al., 2008; Edwards et al., 2012). This biosphere is widespread, with some geological and geographical autochthonism, is genetically and geochemically diverse, and comprises a significant fraction of Earth's total living biomass (Orcutt et al., 2011). High temperatures and pressures, variable pH and salinity conditions, and insufficient access to nutrients, carbon, or energy are potential limiting factors for life in the deep subsurface (Takai and Nakamura, 2011). This theme addresses Challenges 5–7 of the IODP Science Plan.

Several geomicrobiological questions were identified that may be answered by drilling of Indian Ocean sediment. How has uplift of the Himalayas and the monsoon impacted the development of the deep biosphere since the Oligocene? How has the drainage from the Himalayan rivers influenced subseafloor community diversity? How has the subseafloor biosphere been inoculated with terrestrial microorganisms? Are there differences between the Bay of Bengal and Arabian Sea? How are the ecosystems related to the formation of ferromanganese nodules?

Other questions may be answered by drilling Indian Ocean Crust. What is the diversity and biogeography of communities in the very heterogeneous ridge systems? Which microbial communities and functions exist in different crustal provinces and structures? How are they related to hydrogeology and to the alteration of the crust?

In the future, these questions may be addressed if deep biosphere research is incorporated in existing IODP proposals. The community is looking for opportunities to join expeditions conducted by themes 1–3 (above) and to expand objectives by requesting coring through Ancillary Project Letters.

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IODP Workshop on Using Ocean Drilling to Unlock the Secrets of Slow Slip Events

by Laura M. Wallace, Eli A. Silver, Nathan Bangs, Rebecca Bell, Joshu Mountjoy, Stuart Henrys, and Ingo Pecher

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Introduction

Subduction margins produce the largest and most destructive earthquakes and tsunami on Earth. Knowledge of the mechanics of fault slip behavior on subduction thrust interfaces is necessary to understand and mitigate the hazards posed by these major plate boundary features. The observation of episodic slow slip events (SSEs) occurring at many subduction zones worldwide (Fig. 1) is arguably one of the most exciting discoveries in the Earth sciences in the last decade. SSEs involve transient, aseismic slip on a fault, lasting days to months, at a rate intermediate between steady plate boundary displacement rate and seismic slip. Prior to the discovery of slow slip, most studies of fault behavior assumed that slip on faults occurs either as steady creep or suddenly in an earthquake. Geodetic and seismological detection of slow slip and its associated slow seismic phenomena (such as non-volcanic tremor, low-frequency and very-low frequency earthquakes) has transformed our understanding of the spectrum of fault slip behavior (Ide et al., 2007) and has fundamental implications for deformation mechanisms and rheology on subduction megathrusts. Despite the fact that there is now abundant evidence for SSEs at many of the Earth's subduction zones, the physical mechanisms leading to slow slip behavior and the relationship of SSEs to destructive seismic slip on subduction thrusts remain unknown.

A variety of theories regarding the origin of SSEs have been proposed; many consider episodic slow slip as a consequence of high fluid pressures within a conditionally stable frictional regime. These proposed mechanisms for episodic SSE behavior arise largely from theoretical and modeling studies (Liu and Rice, 2005, 2007; Shibazaki and Iio, 2003) and interpretations of physical properties from seismic attributes (Audet et al., 2009; Bell et al., 2010; Kodaira et al., 2004; Song et al., 2009). In many ways, our understanding of the origins of slow slip events has been hampered by the fact that many of the best-studied SSEs worldwide (e.g., Cascadia, Nankai) occur at depths of 30–40 km below the Earth's surface (Dragert et al., 2001; Obara et al., 2004), and scientists must rely on indirect evidence to investigate these fascinating phenomena. However, the discovery of shallow SSEs (at <10 km depth) at subduction margins in New Zealand, central Japan and Costa Rica (Douglas et al., 2005; Outerbridge et al., 2010 Ozawa et al., 2007; Sagiya, 2004; Wallace and Beavan, 2010) highlights the exciting potential for IODP drilling to gain direct access to the SSE source area, and thus to play a key role in unlocking the secrets of SSEs.

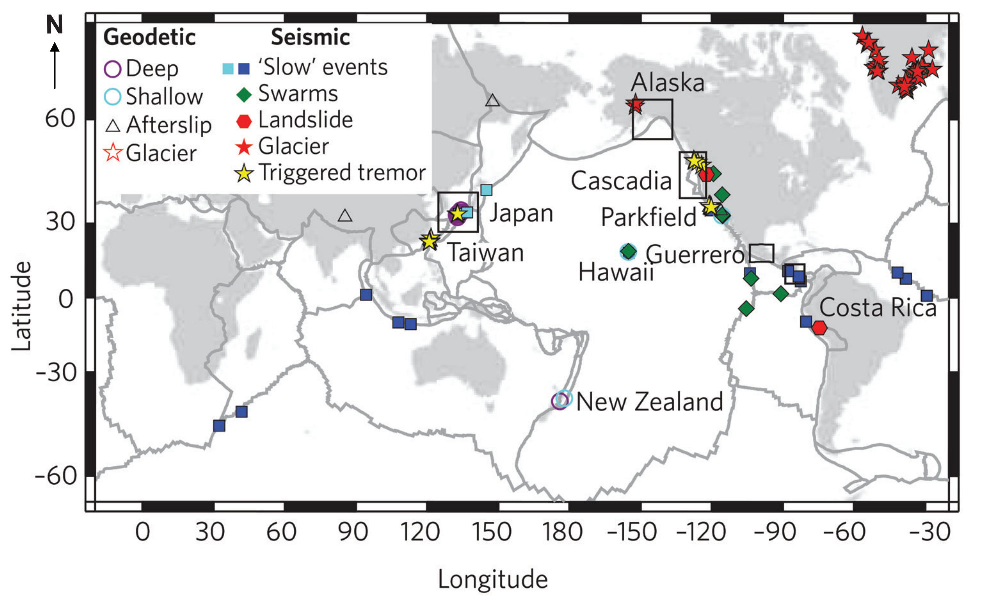

Figure 1. Map showing the global distribution of seismically and geodetically observed slow slip phenomena, from Peng and Gomberg (2010). Note that this map includes slow earthquakes and/or slow slip behavior from all fault types (not just restricted to subduction zones), and slow slip-type phenomena observed in landsliding and glacial settings.

Workshop Goals and Overview

To discuss and develop a plan to use scientific ocean drilling to help advance the emerging and highly topical field of slow slip events, Integrated Ocean Drilling Program (IODP) sponsored a workshop in Gisborne, New Zealand on 1–3 August 2011. The workshop attracted seventy geoscientists from a dozen countries around the world and was also sponsored by the Consortium for Ocean Leadership, the New Zealand Ministry of Science and Innovation, and the U.S. National Science Foundation's (NSF's) GeoPrisms program. Gisborne was chosen as a venue due to its proximity to the source area of shallow slow slip (<5–15 km depth) that occurs at the northern Hikurangi subduction margin in New Zealand. The main three-day workshop was followed by a two-day field trip (sponsored by the New Zealand Ministry of Science and Innovation) from Gisborne to Wellington (Fig. 2), designed to expose participants to the onshore, uplifted components of the Hikurangi forearc and to give participants insights into the geological and tectonic context of slow slip in New Zealand.

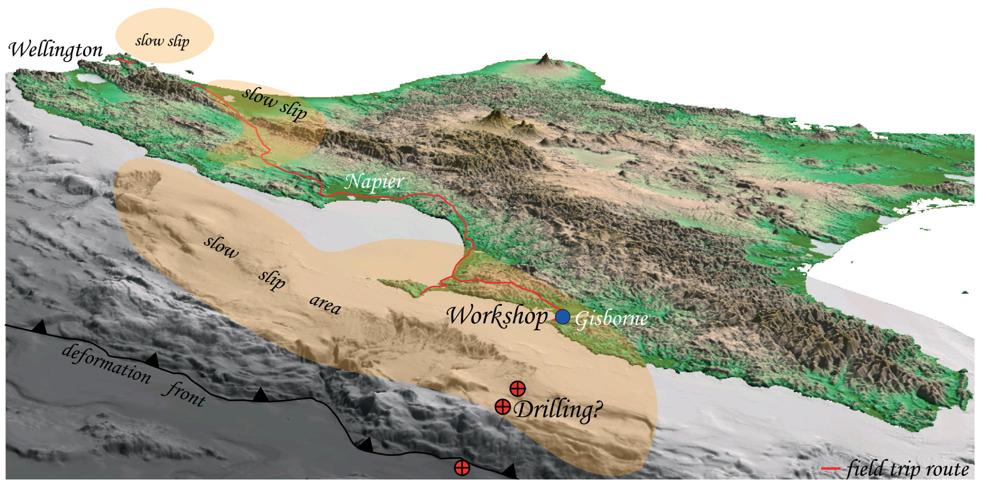

Figure 2. Oblique view of the Hikurangi subduction margin, including locations of slow slip (orange shaded areas), the location of the workshop and field trip route (orange solid line), and some of the proposed slow slip event drilling targets offshore Gisborne.

The primary goals of the workshop were to summarize critical requirements of a drilling program to discern the physical mechanisms responsible for SSE behavior, to develop strategies to achieve the scientific goals, to determine what types of data are needed to develop an effective drilling program, and to identify the expertise and technologies needed for drilling a SSE source area successfully. Oral presentations at the workshop centered around thematic sessions, including (1) observations of and theories for SSE occurrence, (2) lessons learned from previous IODP subduction zone drilling, and (3) potential slow slip drilling targets in New Zealand, Costa Rica, and central Japan. The talks were interspersed each day with breakout discussion sessions and broader group discussions. On the final day, breakout groups developed implementation plans for each location.

Recommendations and Outcomes of the Workshop

Overall, the workshop participants agreed that slow slip events offer a number of compelling scientific questions that can be realistically addressed by IODP drilling. Some of these questions are listed as follows. (1) What does a slow slip zone look like? Is the slip localized to one or two sharp, thin discontinuities, or is slip distributed continuously throughout a zone of finite thickness? (2) Do slow slip events occur in rocks consistent with a conditionally stable frictional regime, as suggested by theoretical studies? (3) Are slow slip events associated with low effective stress due to high pore fluid pressure? (4) Can a single fault patch host both SSEs and "normal" earthquakes? (5) Are SSEs restricted to a specific pressure or temperature range and can they propagate all the way to the trench? Participants concluded that these fundamental questions can be addressed by a strategy that includes conducting geophysical experiments, monitoring shallow instrumented bore holes above SSE source regions, logging and coring of the region above the SSE source and incoming sedimentary section, and, ultimately, by direct sampling and monitoring of the slow slip patch by deep riser drilling. During the workshop the participants discussed generic methodologies to address these questions and developed plans which could be implemented in specific locations around the world.

Auxiliary studies (e.g., non-drilling) are required for any successful SSE drilling program, and these were a major topic of discussion. In summary, participants recommended a broad range of studies with particular emphasis on collocated, integrated studies using geological and geophysical techniques that are designed and constrained with laboratory and numerical modeling. Of particular importance to determining the spatial distribution of SSEs and related seismicity are onshore geodetic and seismic experiments combined with offshore, long-term deployment of ocean bottom seismographs equipped with absolute pressure sensors to monitor seismicity and vertical seafloor deformation during SSEs. Other critical data sets include active source 2D and 3D seismic imaging and wide-angle refraction, passive source studies, heat flow surveys, and multibeam seafloor mapping. These auxiliary data are required to help identify drilling targets and to complement borehole monitoring, core, and log data.

Shallow level borehole monitoring (to detect tilt, strain, seismicity, geochemical, and hydraulic transients) along a transect (Fig. 3) is key to addressing questions related to the spatial distribution of slow slip beneath offshore subduction margins, and to reveal the possible relationship between

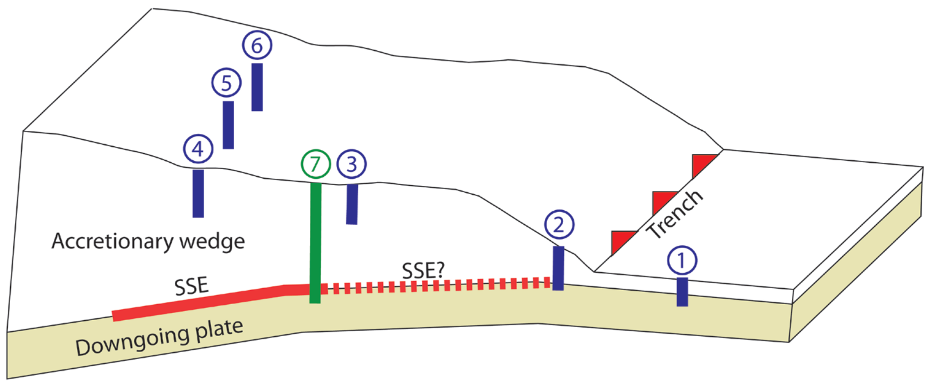

Figure 3. Schematic illustration (not to scale) of a drilling and borehole monitoring scheme which could be applied to address primary SSE questions. See workshop report for further details on the transect design. Note that holes 5 and 6 are positioned off the main transect and are intended for basic monitoring to constrain off-transect variation in SSE behavior. Red patches on the subduction interface show where SSE slip is constrained from onshore instruments. The position of the deep riser hole (#7) should be constrained by current knowledge of the shallowest part of the interface undergoing SSE. In addition to shallow monitoring and sampling of the upper plate, Site 3 would serve as a pilot hole for the deep riser Site 7. Site 1 is primarily intended to core and log the input section on the subducting plate. The dashed red line shows a possible trenchward continuation of SSE behavior. Offshore instrumentation (borehole monitoring and seafloor geodesy) will be needed to constrain the updip limit of SSE.

SSEs and normal seismicity, as well as to discern changes in fluid flow and geochemistry within the upper plate during the SSE cycle. Depending on the monitoring needs and available resources, instrumentation in the boreholes could range from sophisticated, Circulation Obviation Retrofit Kits (CORK) type installations to simpler Simple Cabled Instrument for Measuring Parameters In Situ (SCIMPI) type devices that do not require standard casing installation. Coring and logging along the same transect are required to characterize in detail the lithology, stratigraphy, structure, fluids, and physical properties within the upper plate above the SSE source regions. Of particular importance is comprehensive coring and logging of the entire input section (e.g., undeformed seafloor sediments on the incoming plate), which will reveal the lithologies likely to be found at depth within the SSE source area. Participants developed an idealized shallow (<1–2 km depth) riserless transect design that should achieve the shallow monitoring and coring/logging objectives (Fig. 3). Riser drilling, logging, sampling, and monitoring of the SSE source area would constitute the ultimate, final stage of an SSE drilling program, and would provide the most direct information on the physical conditions (frictional properties, mineralogical composition, fluid pressure conditions, temperature, among others) that lead to and control slow slip event behavior. Targets to intersect SSEs at 5–7 km depth have been identified at some of the shallow SSE locations that were discussed at the workshop. Participants agreed that deep drilling of an SSE source area is within reach and is the ultimate way to solve the mystery of why SSEs occur.

Participants also outlined the characteristics of an "ideal" SSE drilling target. The ideal location must have slow slip occurring somewhat predictably, at depths shallow enough for the source area to be accessible by riser drilling. SSE drilling locations should have a relatively high frequency of SSEs so that multiple cycles can be monitored over a realistic observation period, and the SSEs must be large enough to be measurable and resolvable. Close proximity of the SSE source to the coastline is also advantageous, in order to maximize potential to link with and complement onshore data gathering infrastructure. An SSE target should also have existing 2D seismic reflection profiles to characterize the structure, interface properties, and geological context for the SSEs.

An interesting discovery during the workshop was the realization by participants that the world's best-documented shallow SSEs in Costa Rica, central Japan, and New Zealand bear some striking similarities to each other. All three locations have relatively cold temperatures on the interface in the SSE source (~100°C–150°C), similar SSE durations (generally ~2–3 weeks), comparable equivalent moment magnitudes per event (M_w ~6.5), and a rough, irregular subducting plate (e.g., subduction of seamounts, ridges, or arc volcanoes). We expect that continued comparisons of these three subduction zones begun at the workshop will lead to new insights into the mechanisms behind shallow SSEs.

Following the workshop, some new and/or revised proposals have been submitted to IODP to conduct ocean drilling related to SSE processes for some of the candidate SSE locations. A detailed workshop report is available to view on the IODP website.

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The Towuti Drilling Project: Paleoenvironments, Biological Evolution, and Geomicrobiology of a Tropical Pacific Lake

by James Russell and Satria Bijaksana

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Introduction

Three zones of deep atmospheric convection energize the Earth's heat and moisture budgets: tropical Africa, Amazonia, and the Indo-Pacific. The Indo-Pacific region is by far the largest and most important of these (Fig. 1), and it exerts an enormous influence on global climate (Pierrehumbert, 1999). Lacustrine scientific drilling through International Continental Scientific Drillig Program (ICDP) has provided a suite of lake records from the northern and southern tropics (Fig. 1), providing key insights into the mechanisms responsible for long-term variations in the monsoons at the modern-day limits of the seasonal migration of the Intertropical Convergence Zone (ITCZ) in South America, Africa, and Asia (Fritz et al., 2007; Hodell et al., 2007; Scholz et al., 2007). However, ICDP has not yet provided a long climate record from an equatorial zone of deep convection, nor from the tropical western Pacific.

Lake Towuti (2.75° S, 121.5° E, 561 km^2, 203 m maximum depth) is the largest tectonic lake in Indonesia, and it is part of the Malili lake system, a set of five, ancient (1–2 Myr) tectonic lakes in central Sulawesi (Fig. 2). Lake Towuti's location in central Indonesia provides a unique opportunity to reconstruct paleoclimates and paleoenvironments in the crucially important yet understudied Indo-Pacific Warm Pool (IPWP). Moreover, the Malili lakes have extremely high rates of floral and faunal endemism and are surrounded by one of the most diverse tropical forests on Earth. Drilling in Lake Towuti will document the environmental and climatic context that shaped the evolution of Malili's unique lacustrine and terrestrial ecosystems and their resilience to long-term environmental change. Lake Towuti is surrounded by ultrabasic (ophiolitic) rocks that release high levels of iron, nickel, chromium, and other metals, catalyzing biogeochemical reactions within a diverse, exotic microbial community. Drill core will provide insight into long-term changes in the geomicrobiology of this system, including coupled changes in climate, microbial biogeochemical cycling, carbon storage, metal deposition, and microbial processes operating at depth in the sediment.

Site Description

The clear potential of Lake Towuti to the scientific drilling community was recognized already in 1995 by the Past Global Changes (PAGES) workshop on Continental Drilling for Paleoclimate Records, which designated the Malili Lakes a high-priority drilling target (Colman, 1996). However, only now do we have the requisite site survey information to begin planning a drilling program on Lake Towuti. Over the course of four field seasons we have acquired ~150 meters of sediment core and over a thousand kilometers of CHIRP and airgun seismic reflection data, such that we can now propose the first lake drilling project in Southeast Asia.

Existing sediment cores (10–15 m long) from Lake Towuti reveal large variations in sedimentation at millennial and longer time scales during the past 60 kyr. Variations in sediment metal content are associated with large variations in paleohydrology. These are measured by isotopic indicators, changes in vege-

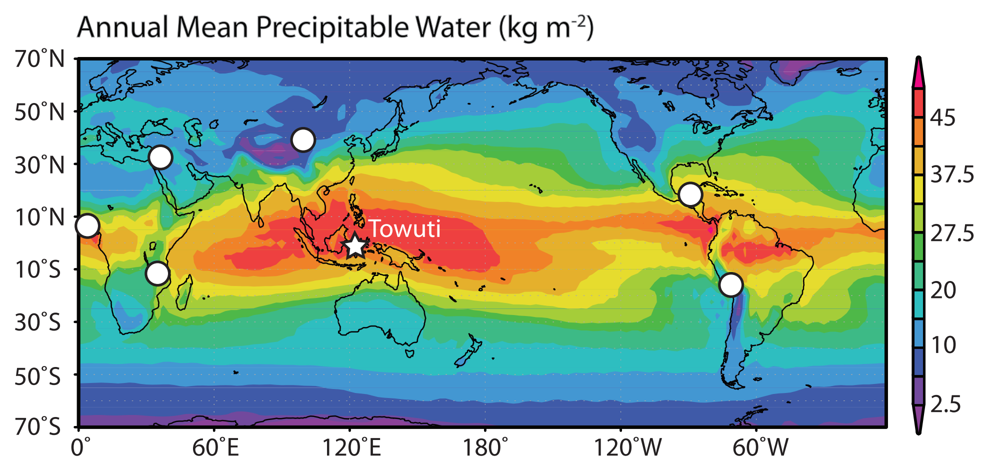

Figure 1. Annual mean precipitable water content of the atmosphere from NCEP Reanalysis (Kalnay et al., 1996), highlighting the importance of the Indo-Pacific to the global atmospheric water cycle. The star indicates the location of Lake Towuti. Circles indicate locations of previous ICDP lake drilling projects in the tropics and subtropics.

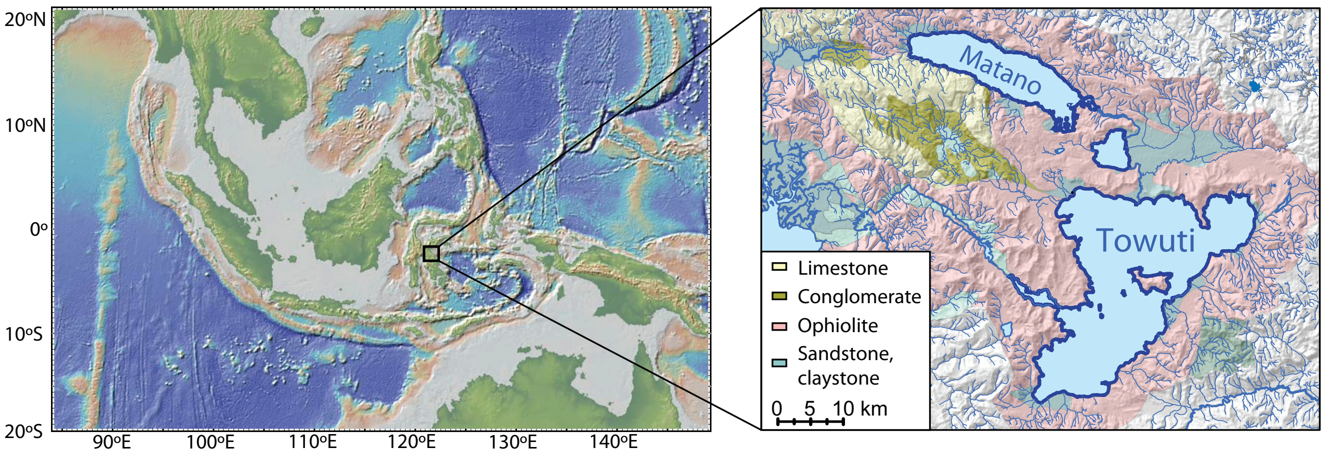

Figure 2. Topographic map of Indonesia and surrounding countries showing the location of the Malili Lakes region within Sulawesi. At right is a simplified geologic map of the Malili Lakes, courtesy of PT Vale-Inco Tbk.

tation observed through fossil pollen, as well as substantial variations in sedimentary organic carbon content and other indicators of lacustrine carbon cycling. All of these indicate coherent linkages between climate, ecosystems, and lacustrine geomicrobiology.

Seismic reflection data document up to 150 meters of stratified lacustrine fill in the basin (Fig. 3), likely spanning the last ~700,000 years. With this abundance of lacustrine sediment, we can test the response of IPWP hydrology across glacial-interglacial variations since the mid-Pleistocene transition. This lacustrine unit is underlain by fluviolacustrine material of a similar thickness that records the history of initial infilling and structural evolution of the Towuti basin. There is no evidence for widespread gas that could pose a drilling hazard, nor extensive tectonic deformation of these sediments; these conditions allow us to optimize our coring locations for critical science objectives. This dynamic setting provides the context in which our science groups developed their hypotheses and questions.

Lake Towuti's climate is influenced by the Australasian monsoons, changes in the Walker Circulation driven from both the Indian and Pacific Oceans, and the location and strength of convection within the ITCZ. Lake level monitoring shows a strong influence of the El Niño-Southern Oscillation (ENSO), and while sediments from Towuti cannot resolve individual El Niño events, the long-term climate variability of Sulawesi is governed by the interplay between meridional monsoon variations and zonally-oriented anomalies that originate in the Walker circulation. Lake Towuti is hosted within a fault-bounded extensional basin along the Matano-Palu Fault, a strike-slip fault system formed in association with the collision between Australia and Eurasia. Bedrock is dominated by the large East Sulawesi Ophiolite (Kadarusman et al., 2004). Lateritic nickel ores that developed on these ultrabasic rocks have attracted the mining industry, with whom we will partner in our proposed work.

Workshop Structure and Findings

To develop the Towuti Coring Project, sixty-two people from nine countries participated in a workshop in Bandung, Indonesia during 26–29 March 2012 to define scientific priorities and logistical demands for deep scientific drilling in Lake Towuti. Presentations on the first day focused on IPWP climate dynamics and history, the structural geological evolution of Sulawesi, and the limnology, geomicrobiology, and evolutionary biology of the lake. Participants spent the following three days in breakout groups to focus on developing the scientific hypotheses and strategies, with breakout groups divided into five themes: paleoclimate, geochronology, geomicrobiology, evolutionary biology, and structural geology. Discussions during day 4 focused on drilling project logistics, planning, and timelines.

The paleoclimate group reviewed extensive data sets from mainland Asia documenting the long-term history of the Asian monsoon, highlighted by loess and speleothem records spanning hundreds of millennia (Wang et al., 2008). These records show a dominant response of the Asian monsoon to orbital precession, yet existing sediment cores from Lake Towuti highlight substantial changes in regional hydrology associated with the Last Glacial Maximum. Drilling long, 700,000-year sequences would allow us to test whether hydrological changes in central Indonesia are driven by tropical insolation or glacial forcing across multiple glacial-interglacial cycles, including changes in the Walker Circulation forced by exposure of the Sunda Shelf and greenhouse gas variations (DiNezio et al., 2011). We could also investigate the amplitude of land surface temperature changes across multiple glacial cycles, its relation to temperature, and the extent to which high-latitude events such as Heinrich and Dansgaard/Oeschger variability influence the hydrology of the maritime continent.

The Malili lakes are ultraoligotrophic systems that contain a unique and fascinating microbial community (Crowe et al., 2008) that dominates the lakes' biology. At present, the high metal and low sulfur content of lake water and sediments fuel a geomicrobiological community in these lakes driven largely by metal cycling. Existing sediment cores suggest large changes in metal deposition through time, with possible impacts on microbial composition, activity, and the lacustrine carbon cycle. Through drilling, we will investigate long-term rates of microbial evolution and ecosystem change in a ferruginous basin. We will further investigate how external forcing—including changes in chemical and physical weathering of the landscape, terrestrial geomorphology, and climate-driven changes in lake mixing—affects Towuti's geomicro-biological community and sediment geochemistry. Indeed, this work will provide important constraints on the behavior of sediment climate proxies in metal-rich, organic carbon-poor sediments

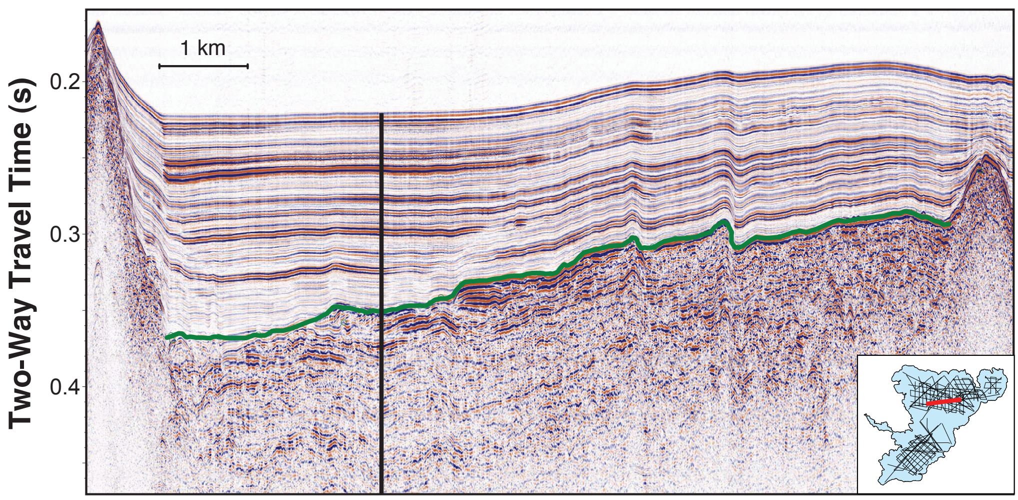

Figure 3. Example of seismic section from northern Lake Towuti (Wattrus et al, unpublished). Inset at bottom right indicates the location of this section (thick red line) within our seismic reflection grid (thin black lines). The boundary between stratified lacustrine sediment (upper unit) and fluviolacustrine sediment (lower unit) is marked by a green line. One hypothetical drilling target is illustrated by the black line.

Lake Towuti is the largest of the Malili Lakes complex, and is situated at the downstream end, with flow from Lake Matano through Lake Mahalona into Towuti. Sarasin and Sarasin (1895) were among the first Western scientists to explore the Malili Lakes, and they noted the lakes' unique fauna. Subsequent work during the twentieth century confirmed the presence of diverse, highly endemic flora and fauna in the Malili Lakes (Rintelen et al., 2011), and data have shown that each of the Malili Lakes contain a locally endemic fauna despite the hydrologic connections between the basin. This could hint at long-term changes in the hydrologic connectivity among these lakes related to movement along the region's numerous and active faults. Drilling in Lake Towuti will allow us to investigate whether tectonic evolution of the Malili Lakes' drainages influenced the timing, rate, and mode of speciation in these basins. Drilling will also elucidate the sensitivity and resilience of central Sulawesi's rainforests to climate, fire, and environmental variability.

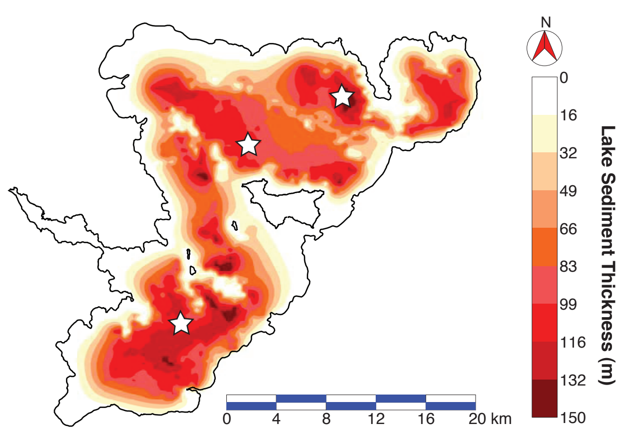

Figure 4. Coring targets (indicated by stars) overlain on a map of the thickness of stratified lacustrine sediment (Wattrus and Russell, unpublished).

Investigations of these areas will require a robust geochronology. The high iron and magnetic mineral content, coupled with little reductive diagenesis, makes Towuti an ideal site for dating sediment cores through paleomagnetic variations. Existing paleointensity data show robust correlation to reference sections from the Sulu Sea (Schneider and Mello, 1996), placing the Towuti chronology on the marine oxygen isotope time scale. Although Towuti is far from major volcanoes, ashes likely derived from the North Sulawesi volcanic field are present in sediment cores and appear common in seismic reflection data. These could provide additional constraint and may also provide a history of large-magnitude eruptions in a poorly studied region.

Participants discussed possible drilling targets to address these issues and whether to drill both the lacustrine and fluviolacustrine sections in Towuti. Participants agreed on the importance of recovering a complete lacustrine and fluviolacustrine section to improve our understanding of the biological and environmental evolution of the Towuti basin. Through these discussions, three primary drilling targets (Fig. 4) were identified:

- a primary site in central Towuti where existing sediment cores and seismic data indicate the most quiescent depositional setting,
- a site situated in northern Towuti to record variations in sediment input from the Mahalona River, to reconstruct the hydrological connectivity of the Malili system, and
- a site in southern Towuti, which is completely dominated by ultramafic rocks and where some of the oldest lacustrine sediments are found.

We are now pursuing pre-drilling scientific activities including improved sedimentological surveys of the Towuti basin, limnological and climate monitoring, and educational and outreach activities within the local community.

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Scientific Drilling in the Basin of Mexico to Evaluate Climate History, Hydrological Resources, and Seismic and Volcanic Hazards

by Erik T. Brown, Josef P. Werne, Socorro Lozano-García, Margarita Caballero, Beatriz Ortega-Guerrero, Enrique Cabral-Cano, Blas L. Valero-Garces, Antje Schwalb, and Alejandra Arciniega-Ceballos

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Introduction

A group of fifty scientists and students from eight countries met on the campus of UNAM (Universidad Nacional Autónoma de México) in Mexico City on 4–8 March 2012 to plan for a program of continental drilling that will address a wide range of ongoing issues and hazards facing the Mexico City region. The initial impetus for the workshop was investigation of a long and continuous climate and ecological record preserved in the lake sediments underlying the city. Workshop attendees included participants with scientific interests in sediment core and borehole instrumentation in this region, including experts in volcanology, seismology, hydrology, geodesy and the associated geological hazards. The workshop was supported by the International Continental Scientific Drilling Program (ICDP) and UNAM.

The Basin of Mexico (Fig. 1; 9600 km^2, 2240 m asl) is a hydrologically closed basin in the central-eastern part of the Mexican Volcanic Belt. Active volcanism around this basin dates from the Oligocene to the present. The lake system of the basin may have developed an association with the basin's closure by emplacement of the Chichinautzin volcanic field in the southern sector of the basin after 780 ka (Mooser et al., 1974; Urrutia-Fucugauchi and Martin del Pozzo, 1993). In any case, continuous deposition has allowed accumulation of thick sequences (>400 m) of lacustrine sediment interbedded with sporadic volcanic horizons.

The hydraulic regime of the former lakes of the Basin of Mexico has been modified since pre-Hispanic times for flood control and agricultural practices. Multiple efforts to drain the basin continued during colonial times in an effort to control periodic flooding and to foster urban development. Mexico City is built upon these lakebeds. Lake Chalco is located on the southernmost sector of the Basin of Mexico; due to its proximity to freshwater sources, Chalco has typically been less saline than other lakes within the basin. This lake was reduced to a small marsh during the nineteenth and early twentieth centuries. It is among the largest blocks of undeveloped agricultural land within the Mexico City megalopolis and is thus a prime target for scientific drilling.

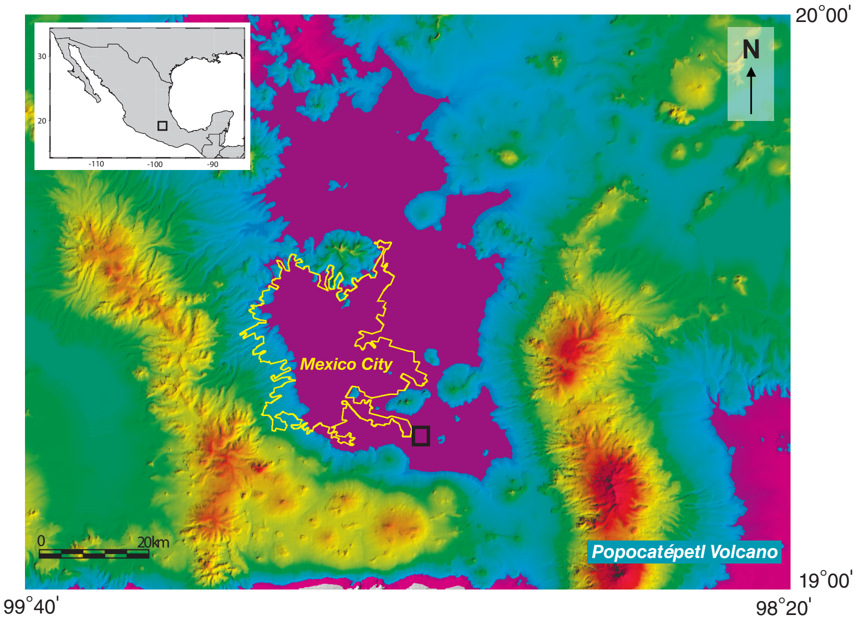

Figure 1. Location map of the Basin of Mexico, showing the location of previous coring at paleolake Chalco.

Sediments from the Chalco Basin have the potential to yield a unique and remarkable record of climate history directly relevant to millions of people. An understanding of past variability in the regional hydrological regime, including variations in monsoonal precipitation, provides a basis for evaluation of ongoing climate change. In addition, the sediments can provide histories of volcanic activity, and their physical properties are relevant to models of seismic wave propagation in the basin as well as to understanding its intense subsidence and regional groundwater resources. Drilling for paleoenvironmental studies can be leveraged and complemented by continuous subsurface geophysical monitoring through instrumented boreholes that will provide additional insights into regional geologic hazards and better groundwater management.

Climate and Ecological History

A significant scientific objective of the Lake Chalco drilling will be obtaining a continuous, high-resolution record of past climates in the continental neotropics over the past ~500 kyr. Previous studies at this location (Fig. 2) have exploited geochemical, geological, and ecological proxy records (Bradbury, 1989; Lozano-Garcia et al., 1993; Lozano-Garcia and Ortega-Guerrero, 1994; Urrutia-Fucugauchi et al., 1994; Caballero-Miranda, 1997; Lozano-Garcia and Xelhuantzi-Lopez, 1997; Caballero and Ortega Guerrero, 1998). This body of research demonstrates that Chalco sediments have the potential to provide unique knowledge of interannual through orbital-scale variations in the North American monsoon and the hydrological balance of the neotropics. Indeed, the cores we expect to retrieve from Chalco would be the longest continuous climate record from tropical North America, and therefore they could become the "type section" to which other records are compared. Southern North America is projected to become more arid in the coming decades and centuries in response to anthropogenically-driven climate change (Seager et al., 2007). In this already dry region, the increasing population pressures water supplies, so more intense drought may pose major societal challenges. Knowledge of past climate fluctuations will add to our understanding of ongoing climate change.

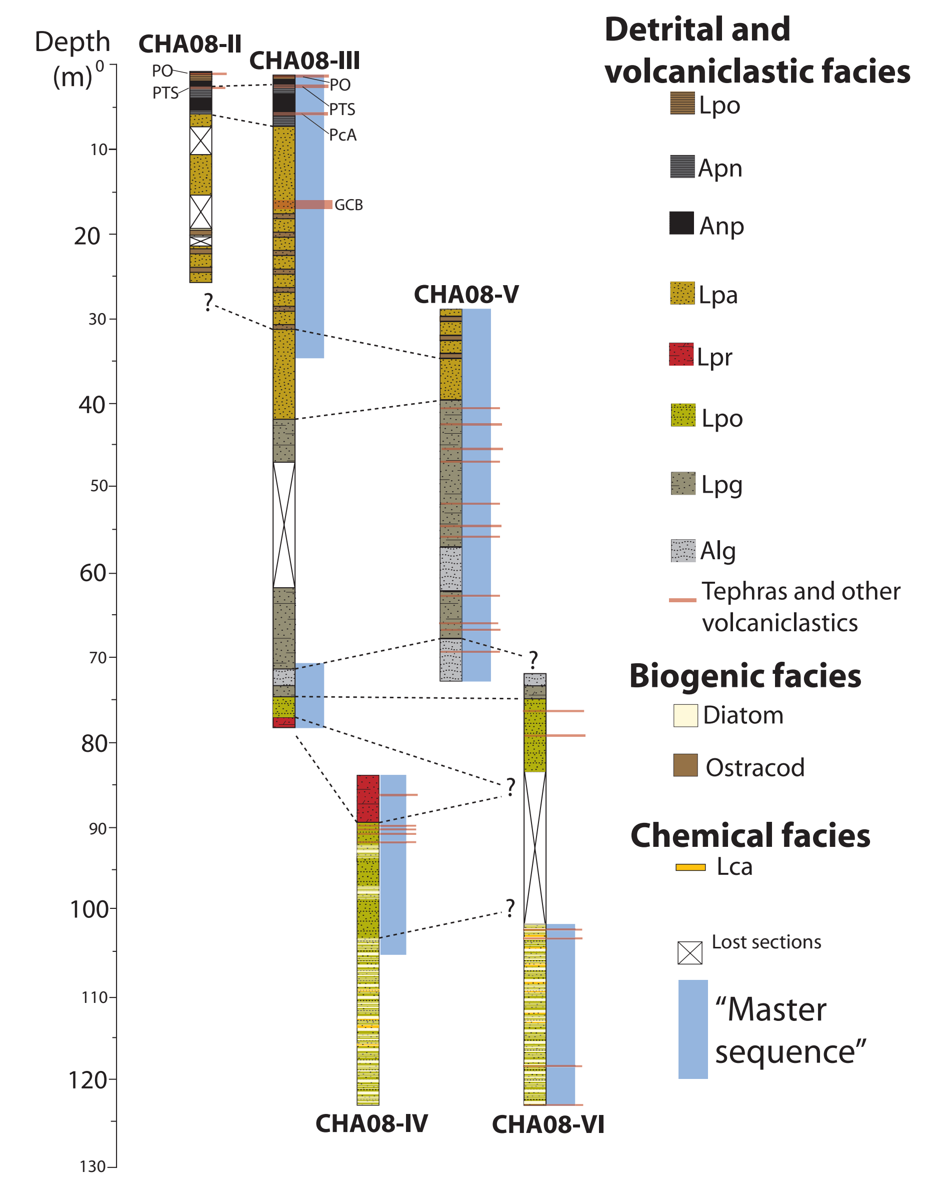

Figure 2. Stratigraphy of core recovered from Chalco in 2008 by UNAM researchers supported by UNAM funding. The base of this section (122 m) has a preliminary age assignment of ~220 ka, suggesting that the full 350–400-m sequence could represent 800 ky of sediment accumulation. Modified from Herrera-Hernandez (2011).

Volcanic History and Hazard

Volcanic activity has occurred throughout the Mexican Volcanic Belt since the Oligocene. For example, Popocatépetl, located at the southeastern end of the Basin of Mexico (35 km from Chalco), is regarded as one of Mexico's most dangerous volcanoes due to the massive eruptions (e.g., 23 ka and 14 ka) preserved in the geological record (Siebe et al., 2004a, 2004b, 2005; Siebe and Macías, 2006; Arana-Salinas et al., 2010). Popocatépetl resumed activity in 1994 after some sixty-five years of dormancy, and it presents a clear hazard to the region.

The drilling program serves needs in two areas.

1. Tephra layers preserved in sediments of the Chalco Basin will provide a unique record of eruptive histories. Precise dating of large and small eruptive events will help to refine the eruptive history from adjacent large stratovolcanoes and will aid in volcanic hazard prediction.

2. Installation of seismic motion sensors at depth will enable monitoring of seismic activity related to Popocatépetl's magma chamber and to aid in evaluating potential future eruptions.

Hydrological Resources and Subsidence

Mexico City utilizes groundwater from its underlying lacustrine aquitard and aquifer. The fine-grained, organic-rich Quaternary lacustrine sequences (Ortega-Guerrero et al., 1997) are highly susceptible to non-recoverable consolidation. Subsidence due to groundwater extraction in the Basin of Mexico was first recognized in the 1890s. In the subsequent 120 years this led to over ten meters of accumulated subsidence in downtown Mexico City, with accompanying damage to housing and urban infrastructure (Ovando-Shelley et al., 2007). During the 1950s subsidence was so widespread in the historic downtown area that extraction wells were relocated to outlying areas, including Chalco (Joint Academies Committee on the Mexico City Water Supply, 1995). In the Chalco region this led to the significant subsidence mentioned above, with current rates of 150–200 mm yr^{1}. Continued withdrawal of groundwater and subsidence has stressed the upper lacustrine sequence, leading to surface fracturing (fracture lengths of ~500 m, with openings up to one meter and vertical displacement as much as two meters), most prevalent at the interface of lacustrine deposits with adjacent volcanic structures. A deep aquifer is also present within the Basin of Mexico; while it remains essentially unexploited, there is ongoing discussion of its potential to meet future needs of the growing city.

The Lake Chalco drilling project will serve multiple needs in this area.

1. physical characterization of sediments associated with aquifers and aquitards to improve understanding and modeling of subsidence, particularly including characterization of the deep (relatively unexploited) aquifer that has not been well-studied;

2. creation of master *in situ* and synthetic logs that can be used for stratigraphic correlation among boreholes within the basin (most of them for groundwater exploitation) and thus allow basin-wide, stratigraphic correlation; and

3. installation of permanent geodetic, hydrologic, and geotechnical monitoring and sampling instruments to characterize changes to groundwater in response to changing well water withdrawal.

Seismic Risks

Seismic hazards are omnipresent in Mexico City; the 1985 M 8.0 earthquake caused well over 10,000 casualties and considerable damage to city's buildings and infrastructure. Continuing activity (most recently, an M 7.4 event on 20 March 2012) poses an ongoing threat to the city. Recent tectonic research has focused on episodic tremor and slip (ETS) events in the Guerreo and Oaxaca segment of the Mid-America trench (Brudzinksi et al., 2007). The subhorizontal geometry of the subducting slab underneath southern and central Mexico effectively widens the sesimogenic area and extends inland the occurrence of ETS events well into the Basin of Mexico.

This project serves two needs in this area: 1) Physical characterization of recovered core material will provide information needed to improve and refine geotechnical earthquake engineering models. 2) Installation of geodetic and seismic sensors—including collocated borehole strain meters, pore pressure sensors, deep seismic and tilt meters, and a surface GPS receiver—in deep boreholes will provide previously unavailable monitoring of micro-seismic activity isolated from surface noise.

Workshop Outcomes

We planned a scientific program that addresses the needs of studies of seismic hazards, volcanoes, hydrology, and paleoclimate/ecology. Prior geophysical studies provide a basis for a broad understanding of the geometry and depth of the basin, but they may be insufficient for selection of drill sites for core recovery. To address this, we are planning and coordinating efforts for magnetic, gravity, and passive seismic surveys to be undertaken in June and July 2012.

The plan is to undertake a two-phase drilling program (proposal to be submitted to ICDP in January 2013, so fieldwork could be as soon as 2014). Phase 1 will drill and log four 500-m wells suitable for use as instrumented boreholes for long-term monitoring of groundwater as well as seismic and volcanic activity. Downhole logs from Phase 1 (in combination with geophysical surveys) can be used to develop strategies for site selection for Phase 2 drilling. The second phase will recover a continuous sequence of core for the physical, chemical, biological, and geological characterization of sediments discussed above.

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The International Ocean Discovery Program—Preparing for Launch

The Integrated Ocean Drilling Program (IODP) international Working Group+ (IWG+) has released a New IODP Framework, establishing the business model for scientific ocean drilling to apply from October 2013 (www.iodp.org/doc_download/3485-new-iodp-framework-17-august-2012). Planning for the transition to the new IODP by the IWG+ (www.iodp.org/international-working-group-plus) has been underway since 2010. The New IODP Framework and a new Science Plan (http://www.iodp.org/science-plan-for-2013-2023) will serve as a foundation for the next decade of international collaboration in scientific ocean drilling.

The U.S. National Science Foundation (NSF) has received approval from the National Science Board for operation of the US operated drilling vessel *JOIDES Resolution* (*JR*) under the new program framework for one year starting October 2013. Based on experiences gained the NSF will then prepare and submit a proposal covering another ten years of internationally co-funded *JR* operations within IODP. Meanwhile, Japan's Ministry of Education, Culture, Sports, Science, and Technology (MEXT) will develop long-term funding models for the riser-drilling vessel *Chikyu*, and the European Consortium for Ocean Research Drilling (ECOR) will seek approval from its eighteen members for continued funding of its fiscal contribution to program platforms including its own operations of Mission Specific Platforms (MSPs).

Among the significant changes from the current IODP outlined in the Framework document is the replacement of central program management and platform scheduling by IODP Management International with three Facility Governing Boards (FGBs)–one for each platform–to manage and schedule platform operations. NSF will establish an IODP Support Office to coordinate a single scientific advisory structure (SAS) that will advise all three FGBs and support other central program activities. MEXT and *Chikyu* owner JAMSTEC (Japan Agency for Marine-Earth Science and Technology) will establish a Project Partnership Office to develop funding and facilitate large-scale collaborations, and to support SAS processes for the riser drilling projects. A non-executive IODP Forum consisting of community scientists, and to include representatives from funding agencies, platform operators and others, will be the custodian of the Science Plan and a venue for exchanging views on the scientific progress of the Program provided by the three drilling platforms. The Australia-New Zealand IODP consortium (ANZIC), IODP China, IODP India, IODP Korea, and the most recent IODP member, Brazil, are all preparing for their membership in the new IODP under this new program structure.

MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

ECORD Managing Agency

Australian and New Zealand IODP Consortium

Lake Ohrid Drilling Postponed

icdp

Coring operations at Lake Ohrid, Macedonia were planned to be conducted from September to November this year. However, during the mobilization from the United States to Europe the container vessel *MSC* Flaminia caught fire and was evacuated almost in the middle of the Atlantic Ocean. The vessel is currently manned by a salvage crew and the fire is extinguished, but the status of the cargo is still unclear. Due to this delay and potential damage or loss of coring equipment, a start of the drilling operation at Lake Ohrid this year is highly unlikely and has been postponed.

CHIKYU+10 International IODP Workshop

21–23 April 2013, Tokyo, Japan

For more information: Chikyu10@iodp.org

IODP INTEGRATED OCEAN DRILLING PROGRAM

JAMSTEC

D/V *Chikyu*, owned and operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), is one of the three scientific drilling platforms that will continue to operate in the next phase of the International Ocean Discovery Program (IODP). Its deep riser drilling capability offers unique opportunities to address a number of key challenges described in the IODP New Science Plan.

The workshop aims to identify science priorities to be addressed using the *Chikyu* over the next decade. The outcome of the workshop will influence JAMSTEC's decisions as it prepares *Chikyu*'s next Five-Year Plan under the auspices of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), as well as *Chikyu*'s long-range plan for the next ten years.

An international steering committee of approximately fifteen carefully chosen members will design and organize the workshop facilitated by IODP Management International (IODP-MI). Truly deep targets such as the ongoing NanTroSEIZE require long-term commitment, careful planning and project management. In the present financial outlook, there can likely be a few riser projects of the

NanTroSEIZE-scale in the coming ten years, thus the need for international prioritization based on realistic projections.

The workshop will discuss all the active riser drilling proposals as well as new ideas with technical feasibility and scientific excellence and will map onto decadal roadmaps. Details will be announced on the IODP website.

UK Joins the International Continental Scientific Drilling Program

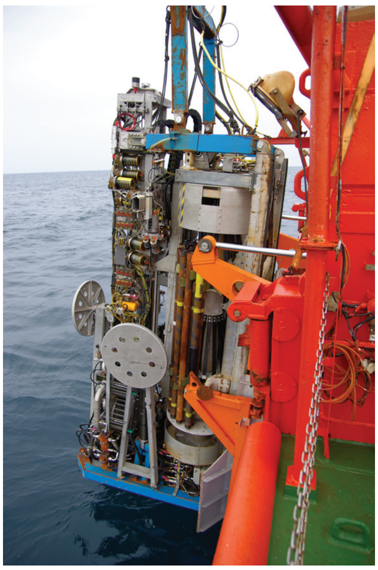
The UK has become a full member of the (International Continental Scientific Drilling Program (ICDP) in effect from April 2012. A launch meeting attended by seventy scientists was held at British Geological Survey, Nottingham, in July 2012. The UK is an active member of the (IODP) but has never before participated as a formal member of the ICDP, despite involvement of scientists in a number of programs. It is important that UK scientists are able to participate fully in ICDP to initiate programs and to allow them to collaborate with existing international science programs involving ICDP. The British Geological Survey (BGS) agreed to invest in membership of the ICDP on behalf of the UK's Earth Science Sector to build national capability for the geoscience community. The membership allows UK scientists to now fully participate within ICDP projects via access to key geological sections in order to gain information on processes that cause global change, to understand the controls on resource development, to help monitor and model natural hazards (through borehole monitoring), and to investigate fluid-related biological processes in the sub-surface. UK geoscientists will now be fully engaged in both IODP and ICDP and can help develop synergies between these programs. At the same time the BGS will work with European countries through ECORD-IODP (http://www.ecord.org/) and the European members of ICDP to create a European infrastructure for scientific research drilling.

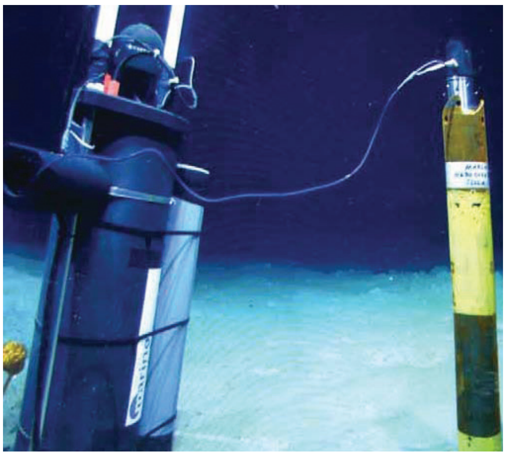
More information can be found on the ICDP-UK web site: http://www.bgs.ac.uk/icdp.

A small group of UK scientists have been nominated to act as ICDP-UK convenors for the first phase of UK membership. UK geoscientists can contact members from this group for further information: http://www.bgs.ac.uk/icdp/ukconvenors.html.

First Generation of MeBo-CORKs Extend Capabilities

The seafloor drill rig MeBo, developed at MARUM, University of Bremen, Germany, is capable of drilling 75 mbsf in water depths exceeding 2000 meters (http://www.marum.de/en/Sea_floor_drill_rig_MeBo.html). Recently, the first long-term observatories for MeBo boreholes were developed and deployed on active mud volcanoes in the Nankai Trough subduction zone, Japan. After hole completion with MeBo, the drill pipe is left in the ground as casing, and an instrument of the same geometry is added to "CORK" the hole (i.e. obviate communication between hole and overlying seafloor). The self-contained instrument comprises pressure and temperature transducers, a data logger, and an acoustic modem so that data download from ships of opportunity is feasible. In the lower portion of the instrumented rod, a needle-shaped drop weight connected to hydraulic tubes is released acoustically and penetrates the sediment at the bottom of the hole. The tubes primarily serve to monitor pressure but can also be utilized to extract fluid samples if the simple MeBo-CORK instrument is disconnected at its hot stab and gets replaced by a seafloor unit with an osmo-sampler. The hot stab connection ensures that instruments can be replaced easily by remotely operated underwater vehicle (ROV) and allows holes to be used repeatedly. Given that seafloor drills are envisaged as an affordable mission-specific tool in IODP from 2013 onwards, these first generation MeBo-CORKs offer many opportunities for the scientific community.





Left: MeBo seafloor drill rig; Right: MeBo-CORK seafloor unit after ROV visit. Plastic tube right of pressure housing hosts osmo-sampler.

CDEX Successfully Completes Japan Trench Fast Drilling Project (J-FAST)

IODP Expeditions 343 and 343T were successfully completed by Center for Deep Earth Exploration (CDEX), with the Expedition Science Party overcoming technical and weather challenges to enable D/V *Chikyu* to set a new record drilling depth in scientific ocean drilling with a total of 7768.5 m measured from the rig floor (7740 m below sea level). Most importantly, the science party was able to obtain core samples from the fault zone and install borehole observatories to monitor conditions at the fault.

The J-FAST Expedition demonstrated IODP's ability to respond quickly to learn more about the devastating Great East Japan Earthquake of 11 March 2011. Planning for J-FAST started soon after the earthquake and after repairs to *Chikyu* from damage caused by the tsunami, the Expedition began at the port of Shimizu on 1 April 2012. Expedition 343T, J-FAST II, was an extension of the project approved by IODP SAS and funded by MEXT/JAMSTEC to give the Science Party time to install the borehole observatories after earlier delays prevented their deployment during the initial Expedition.

The J-FAST expedition represents the first time that frictional heat produced by the fault slip of a great subduction zone earthquake could be measured at the fault zone. The installed borehole observatories will enable scientist to monitor the temperature of the fault zone and study the physics of the earthquake at the fault.

DEBI RCN Meeting at Bremen

On 7–9 June 2012, sixty researchers from five countries gathered at MARUM, University of Bremen, Germany (www.marum.de), for this year's Dark Energy Biosphere Institute (DEBI) Research Coordination Network (RCN) Meeting. Lectures and training workshops including IODP cores focused on ocean crust processes and consequences for subseafloor life. The science conference part of the Bremen meeting provided a forum for presenting and discussing the most recent results in ocean crust processes and identifying the most pressing challenges that lie ahead. Specific focus was on (1) crustal heterogeneity and fluid flow, (2) ocean-crust interactions, and (3) role of microbes in rock alteration.

The 3-day meeting had equal time for a science conference and a training workshop. Both parts were focused on recent developments in understanding ocean crust formation and evolution, ocean-crust exchange, and detection of sub-basement life and microbe-rock interactions. The conference portion provided a forum to present research activities and findings to a broadly trained but scientifically focused audience. The training workshop served as a means to further educate scientists and students. The aim was to present key research techniques and methods commonly employed, to discuss the advantages and drawbacks for specific applications, to produce consensus recommendations, and to make available detailed lab and field protocols. A visit to the IODP Bremen Core Repository (BCR) (http://www.marum.de/en/IODP_Bremen_Core_

Southwest Pacific Ocean IODP Workshop

8–11 October 2012, Sydney, Australia
For more information, write: Neville.Exon@anu.edu.au

This workshop, to be held at Sydney University, will address global geoscience problems in the Southwest Pacific Ocean by building on existing and new geophysical and geological information including earlier scientific drilling. This news item reports on progress since the announcement of the workshop in the April 2012 edition of *Scientific Drilling*. The workshop themes are largely those in the new science plan:

1) Climate and Ocean Change: Reading the Past, Informing the Future
Co-chairs: Tim Naish (NZ) and Jim Kennett (USA)

2) Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems
Co-chairs: Steven D'Hondt (USA) and Ken Takai (Japan)

3) Earth Connections: Deep Processes and Their Impact on Earth's Surface Environment
Co-chairs: Richard Arculus (Australia) and Mike Gurnis (USA)

4) Earth in Motion: Processes and Hazards on Human Time Scales
Co-chairs: Laura Wallace (USA) and Jim Mori (Japan)

5) Marine Resources: Opportunities and Responsibilities
Co-Chairs: Alex Malahoff (New Zealand) and Clinton Foster (Australia)

Funding has been made available by IODP-MI, U.S. Science Support Program (USSSP), ANZIC and Japan Drilling Earth Science Consortium (J-DESC). The event was advertised in *EoS* in May, and on the IODP (www.iodp.org) and ANZIC (www.iodp.org.au) web sites, and it has generated considerable interest. As of early August, we expected more than eighty participants, with a large proportion being from outside Australia and New Zealand.

The workshop will provide a forum to review the latest work in the region, briefly outline possible future IODP expeditions, coordinate activities associated with schedul-ed and proposed geoscience research cruises in the area, and set up working groups to develop proposals for post-2013 IODP expeditions. It will also explore co-investment opportunities between IODP partners and other parties, including industry. There is no doubt that the Workshop will succeed in its main aim of starting to build coherent and well-integrated proposals for the International Ocean Discovery Program starting in late 2013.

Repository.html) was also included to show first-hand the rock samples currently available for study. Workshop participants learned details of shipboard core recovery, sampling, and other techniques pertinent to subseafloor biosphere expeditions.

Further information: http://www.darkenergybiosphere.org/RCN/meetings/2012.html

ECORD Summer School 2012 in Canada

The joint ECORD/ICDP/IODP-Canada Summer School on cryosphere dynamics took place from 5–21 July in Montréal, Québec. Nineteen participants gathered from universities in Belgium, Canada, Denmark, Greece, Sweden, the Netherlands, and the UK.

The first week consisted of classes and workshops presented by invited lecturers at GEOTOP (University of Québec in Montréal), focused on reconstructing the cryosphere and climate change in the Cenozoic from different perspectives and time scales, using modeling, geomorphology, palaeomagnetism, and terrestrial and marine core records. During the second week, the summer school travelled to the north shore of the St. Lawrence River for a 5-day field excursion. At Lac Walker, an ancient fjord now the deepest known lake in Québec, participants carried out surveys using CTD profiles, took underwater gravity cores and explored the nearshore surface sediments with a remotely operated submarine. Students also conducted sub-bottom acoustic profiling and high-resolution multibeam bathymetry; and they were guided through numerous outcrops of Quaternary sediments. Upon returning from the field, students participated in interactive exercises and classes on microfossil analysis, sedimentary analysis, seismic interpretation, time series analysis, radiogenic and stable isotope methods.

The Canadian summer school offered an excellent opportunity for students of diverse nationalities and academic backgrounds to collaborate and learn about the current understanding of cryosphere dynamics and methods used to reconstruct past climate change.

Section of Holocene deposits along the north coast of the St. Lawrence estuary.

IODP/ICDP at the International Geological Congress (IGC) in Brisbane

The International Geological Congress in Brisbane (6–10 August 2012) attracted more than 6000 participants and over 200 exhibitors, including a joint IODP-ICDP exhibition booth. It was a successful conference, and many international scientists turned out for IODP- and ICDP-related events.

There were thirty-six major themes covered in the symposia and some excellent plenary talks. The IODP Symposium was part of the Marine Geoscience and Paleoceanography Theme, and attracted thirteen oral presentations and several poster presentations. The audience size varied from forty to seventy, and the talks generated favorable comments. Keynote addresses were by Neville Exon on general aspects of IODP and its future, Dorrik Stow on the Mediterranean Outflow Expedition 339, and Mike Mottl on porewater chemistry in ocean drilling. The audience was particularly large when Jody Webster spoke on aspects of the Great Barrier Reef Expedition 325. A number of other IODP-based talks were given in various other symposia, thus getting the word about IODP out to a wider audience. ICDP held an evening ICDP Primer that was well attended.

The IODP/ICDP booth was staffed by Catherine Beasley of ANZIC, Thomas Wiersberg and Uli Harms of ICDP, and Miyuki Otomo and Jamus Collier of IODP-MI. Many people were deeply interested, and many scientists with ocean drilling experience came by and enlivened the discussions. Carol Cotterill of ECORD deserves particular thanks for her generous help. Many visitors asked about the planning for a Mohole in the next phase of IODP. Visitors helped themselves to all of the available information and scientific material, a sign of widespread interest.

Miyuki Otomo, Neville Exon, Catherine Beasley and Carol Cotterill at the IODP booth at IGC.

Schedules

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

	ESO Operations	Platform	Dates	Port of Origin
1	347- Baltic Sea Paleoenvironment	MSP	Spring/Summer 2013	TBD
	USIO Operations *	**Platform**	**Dates**	**Port of Origin**
2	344 - Costa Rica Seismogenesis Project 2 (CRISP)	*JOIDES Resolution*	23 Oct.–11 Dec. 2012	Balboa, Panama
3	345 - Hess Deep Plutonic Crust	*JOIDES Resolution*	11 Dec. 2012–12 Feb. 2013	Puntarenas, Costa Rica
4	341 - Southern Alaska Margin Tetonics, Climate & Sedimentation	*JOIDES Resolution*	29 May–29 Jul. 2013	Victoria, Canada
5	346 - Asian Monsoon	*JOIDES Resolution*	29 Jul.–28 Sep. 2013	Valdez, U.S.A.
	CDEX Operations **	**Platform**	**Dates**	**Port of Origin**
6	337 - Deep Coalbed Biosphere off Shimokita	*Chikyu*	25 Jul.–30 Sep 2012	Shimizu, Japan
7	338 - NanTroSEIZE Plate Boundary Deep Riser - 2	*Chikyu*	1 Oct.–13 Jan. 2013	Shimizu, Japan
8	348 - NanTroSEIZE Plate Boundary Deep Riser	*Chikyu*	TBD	TBD

MSP=Mission-Specific Platforms TBD=to be determined
* 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	Campi Flegrei	Since Jul. 2012	Naples, Italy
2	GONAF	Sep. 2012–Jul. 2013	Istanbul, Turkey
3	Songliao Basin	Nov. 2012–Nov. 2013	Daqing, China
4	Lake Ohrid	May 2013–Jun. 2013	Macedonia, Albania
5	COREF	Jul. 2013–Sep. 2013	Ryukyu Islands, Japan
6	Human Origins	Jul. 2013–Jan.2014	Kenya, Ethiopia, Africa