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# Scientific Drilling

## Reports on Deep Earth Sampling and Monitoring

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# Editorial Preface

**Dear Reader,**

In a world of socio-economic challenges the need for scientific drilling has never been greater. Scientific Drilling can deliver answers to fundamental and societal relevant questions about climate and environmental change, natural disasters forecast and prevention, and the search for alternative resources. This spring 2014 issue of your journal Scientific Drilling summarizes some of the recent scientific and technical progress achieved through the International Ocean Discovery Program (IODP) and the International Scientific Continental Drilling Program (ICDP).

Today most of our growing demand for energy is satisfied by conventional hydrocarbons with known, but controversial debated impact on climate. Climate modeling requires reliable input parameter that can be delivered from climate archives provided by scientific drilling. We report on drilling activities that shed new light to the environmental and biological evolution of North Pond nearby the Mid-Atlantic Ridge (IODP Expedition 336, page 13) and Lake Ohrid in Macedonia (page 19). Expedition 336 was executed to address fundamental microbiological questions concerning the nature of the subseafloor deep biosphere in oceanic hydrological, geological, and biogeochemical context. Sediments in Lake Ohrid, Europe's oldest lake have been retrieved to study the influence of major geological and environmental events on the biological evolution of lake taxa. A workshop served to evaluate available biogeochemical data to foster thermodynamic and metabolic activity modeling and measurements and to identify regional targets in the marine realm (page 61) and drilling prospects in the Southwest Pacific (page 45) discuss potential targets for future scientific drilling projects.

Moreover, conventional energy resources are not only limited or have a climate/environmental impact – they are also unequally distributed worldwide, driving the search for alternatives. The Japan Beyond-Brittle Project will investigate the feasibility of developing enhanced geothermal system for energy production from the brittle–ductile transition zone (page 51). New and innovative solutions are needed to push the limits of feasibility for such technically challenging tasks. A technical report describes how core samples can be retrieved without releasing the in situ hydrostatic pressure during core recovery (page 37).

Human's habitat is constantly endangered by rare but violent geodynamic events such as earthquakes, volcanic eruptions, and tsunamis. Therefore understanding of the processes driving these disasters will remain a prime goal for earth science. Papers on seismic monitoring in a shallow borehole in Italy (page 31) and about IODP Expedition 338 in the Nankai Trough offshore Japan (page 1) report on characterization of the seismic underground in earthquake-prone areas. In the Northern Apennine of Italy a near fault observatory has been installed by installing connecting multi-sensor stations in shallow boreholes to collect recordings of short low magnitude earthquakes. Expedition 338 extended an existing hole from 856 to 2006 m by riser drilling to study the inner wedge of the Nankai accretionary prism and drilled several riserless holes to investigate fault mechanics and seismogenesis along a subduction megathrust.

Your Editors
**Ulrich Harms, Thomas Wiersberg, Gilbert Camoin, James Natland, and Tomoaki Morishita**

## Aims & Scope

**Scientific Drilling (SD)** is a multidisciplinary journal focused on bringing the latest science and news from the scientific drilling and related programs to the geosciences community. Scientific Drilling delivers peer-reviewed science reports from recently completed and ongoing international scientific drilling projects. The journal also includes reports on Eng-ineering Developments, Technical Developments, Workshops, Progress Reports, and news and updates from the community.

## Editorial Board

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**Cover figures:** Deep Lake Drilling System on Lake Van, Macedonia. Photos: Niklas Leicher (Cologne University), Anke Neubert (Kiel University), Stefan Schorr (Cologne University)

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# IODP Expedition 338: NanTroSEIZE Stage 3: NanTroSEIZE plate boundary deep riser 2

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**Abstract.** The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is designed to investigate fault mechanics and seismogenesis along a subduction megathrust, with objectives that include characterizing fault slip, strain accumulation, fault and wall rock composition, fault architecture, and state variables throughout an active plate boundary system. Integrated Ocean Drilling Program (IODP) Expedition 338 was planned to extend and case riser Hole C0002F from 856 to 3600 meters below the seafloor (m b.s.f.). Riser operations extended the hole to 2005.5 m b.s.f., collecting logging-while-drilling (LWD) and measurement-while-drilling, mud gas, and cuttings data. Results reveal two lithologic units within the inner wedge of the accretionary prism that are separated by a prominent fault zone at ~ 1640 m b.s.f. Due to damage to the riser during unfavorable winds and strong currents, riser operations were suspended, and Hole C0002F left for re-entry during future riser drilling operations.

Contingency riserless operations included coring at the forearc basin site (C0002) and at two slope basin sites (C0021 and C0022), and LWD at one input site (C0012) and at three slope basin sites (C0018, C0021 and C0022). Cores and logs from these sites comprehensively characterize the alteration stage of the oceanic basement input to the subduction zone, the early stage of Kumano Basin evolution, gas hydrates in the forearc basin, and recent activity of the shallow megasplay fault zone system and associated submarine landslides.

## 1 Introduction

Subduction zones generate Earth's most destructive earthquakes, but much of what we thought we knew about great earthquakes, and the tsunamis they generate, was turned upside down by the 2004 Sumatra and 2011 Tohoku events. To better understand seismogenesis and rupture propagation along subduction plate boundary faults, the Integrated Ocean Drilling Program (IODP) implemented drilling as part of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) along a transect offshore of the Kii Peninsula, Honshu, Japan (Tobin and Kinoshita, 2006; Figs. 1, 2).

The Nankai Trough is formed by subduction of the Philippine Sea Plate to the northwest beneath the Eurasian Plate at a rate of ~ 4.1–6.5 cm $\mathrm{yr}^{-1}$ (Fig. 1) (Seno et al., 1993; Miyazaki and Heki, 2001), and Shikoku Basin oceanic plate sediment is actively accreting at the deformation front. In the seaward portion of the Kumano forearc basin, the genic zone lies < 6000 m below sea floor (m b.s.f.) (Nakanishi et al., 2002). The Nankai Trough region has a 1300 yr historical record of recurring great earthquakes that are typically tsunamigenic, including the 1944 Tonankai $M_\mathrm{w}$ 8.2 and 1946 Nankai $M_\mathrm{w}$ 8.3 earthquakes (Fig. 1; Ando, 1975; Hori et al., 2004, Baba et al., 2006).

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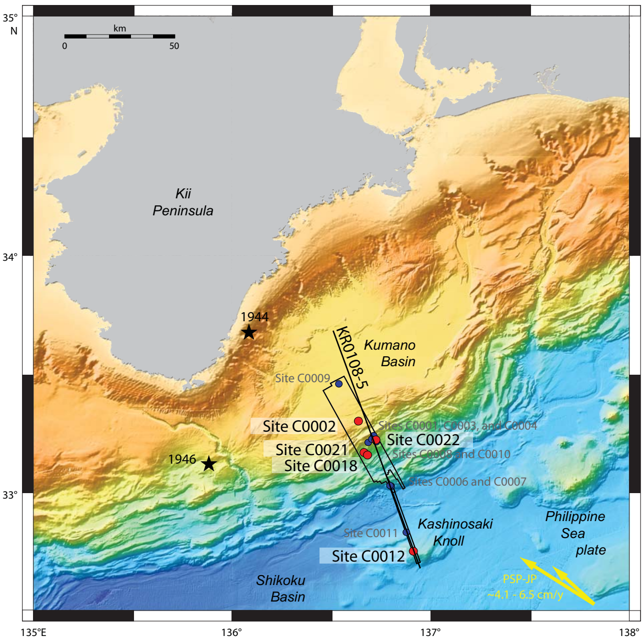

**Figure 1.** Map of the NanTroSEIZE region showing all Stage 1, 2, and 3 drill sites. Red = Expedition 338 sites, blue = NanTroSEIZE Stage 1 and 2 sites. Black outline = region with 3-D seismic data, yellow arrows = estimated far-field vectors for motion of Philippine Sea Plate (PSP) with respect to Japan (JP) (Seno et al., 1993; Heki, 2007). Stars = epicenter locations of 1944 and 1946 tsunamigenic earthquakes. Black line = KR0108-5 seismic reflection line shown in Fig. 2.

Along the Nankai margin, high-resolution seismic reflection profiles across the outer wedge of the accretionary prism (including a ~11 km × 55 km 3-D seismic reflection volume; Moore et al., 2009), clearly document a large out-of-sequence-thrust fault system (the megasplay fault; Park et al., 2002; Fig. 2) that branches from the plate boundary close to the updip limit of inferred coseismic rupture in the Tonankai earthquake (Fig. 1). The megasplay system is active and it may accommodate an appreciable component of plate boundary motion, but the partitioning of strain between the décollement zone and the megasplay system (Fig. 2) and the mechanics of fault slip as a function of depth and time on the megasplay remain poorly understood. The main objectives of the NanTroSEIZE project include documenting the role of the megasplay fault in accommodating seismic and interseismic plate motion and characterizing its mechanical and hydrologic behavior.

During stages 1 and 2 of NanTroSEIZE (IODP Expeditions 314, 315, 316, 319, 322, 332, and 333), eight riserless drilling sites and one riser drilling site targeted the incoming Philippine Sea Plate, the frontal thrust region, the midslope megasplay fault region, and the Kumano forearc basin (Figs. 1, 2; Kinoshita et al., 2009; Saffer et al., 2010; Saito et al., 2010; Kopf et al., 2011; Henry et al., 2012).

NanTroSEIZE Stage 3 began with IODP Expedition 326, during which casing was installed in Hole C0002F to 860 m b.s.f. (Expedition 326 Scientists, 2011). Although IODP Expedition 338 drilling was planned only to deepen Hole C0002F, we also conducted riserless coring and logging at Site C0002 and four additional sites (Table 1).

Site C0002 is planned to access the plate interface fault system where it is believed to be capable of seismogenic locking and slip, and to have slipped coseismically in the Tonankai earthquake (Ichinose et al., 2003). This fault system also includes the region where a cluster of very low frequency (VLF) seismic events occurred in 2004–2005 (Ito and Obara, 2006) and the first tectonic tremor recorded in an accretionary prism setting was found (Obana and Kodaira, 2009). To access, sample, and monitor these deeper zones, Hole C0002F will be deepened in 2013–2015, with the ultimate goals of penetrating the megasplay fault and installing a long-term observatory.

In this paper we present the initial results of logging, cuttings, mud gas and coring during Expedition 338. We characterize the petrophysical properties and lithological/structural associations determined from our log, cuttings and core data.

## 2 Scientific objectives of Expedition 338

The fundamental objectives of Expedition 338 are:

- To sample the forearc basin sediment and gas hydrate zone, the Kumano forearc basin – accretionary prism unconformity, and the upper portion of the inner wedge to (1) determine the composition, age, stratigraphy, and internal style of deformation; (2) characterize the gas hydrate zone in the forearc basin; (3) reconstruct thermal, diagenetic, and metamorphic history; (4) investigate the mechanical state and behavior of the formation; and (5) characterize the overall structural evolution of the accretionary prism.

- To characterize the sedimentary section and mass transport deposits (MTDs) in a slope basin seaward of the megasplay fault at sites C0018 and C0021 (Figs. 3, 4) to understand the nature of MTDs and their sliding dynamics and tsunamigenic potential.

- To target the uppermost 400 m b.s.f. near the projected fault tip of the megasplay fault. The seismic reflection data had previously identified this region as the tip of the megasplay fault that emplaced the block drilled at Site C0004 over slope basin strata (Fig. 5; Moore et al., 2009). This megasplay fault is thought to coincide with the outermost rupture area of the Tonankai earthquake, and its slip was likely in part responsible for the associated devastating tsunami (Park et al., 2002; Moore et al., 2007).

- To characterize the sedimentary section and the upper portion of the oceanic crust (Site C0012) in the Shikoku

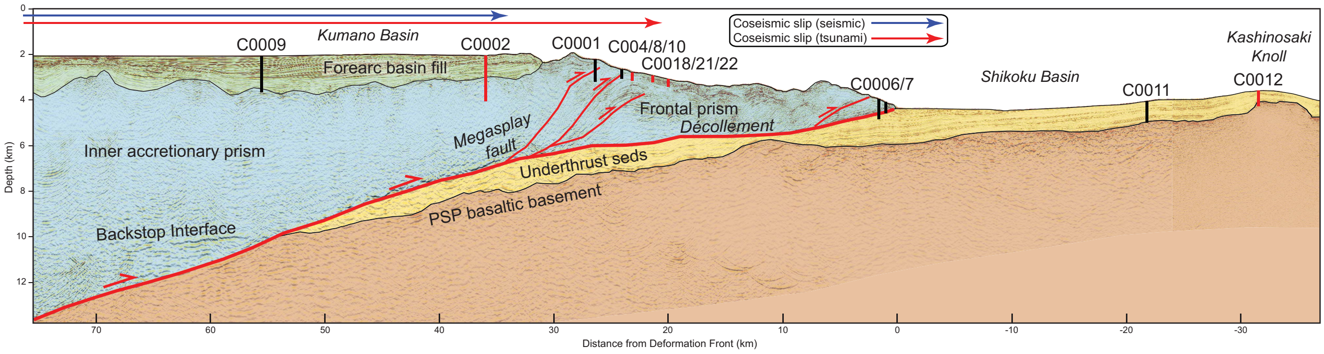

**Figure 2.** Regional 2-D seismic line showing Expedition 338 sites (red) in relation to NanTroSEIZE Stage 1 and 2 sites (black). PSP = Philippine Sea Plate. Lines at top with arrows indicate seaward distribution of coseismic slips 1944 and 1946 earthquakes estimated from tsunami inversion (red; Tanioka and Satake, 2001) and seismic waveform inversion (blue; Ichinose et al., 2003; Kikuchi et al., 2003). Location shown in Fig. 1. Modified from Park et al. (2002, 2008) and Nakanishi et al. (2008).

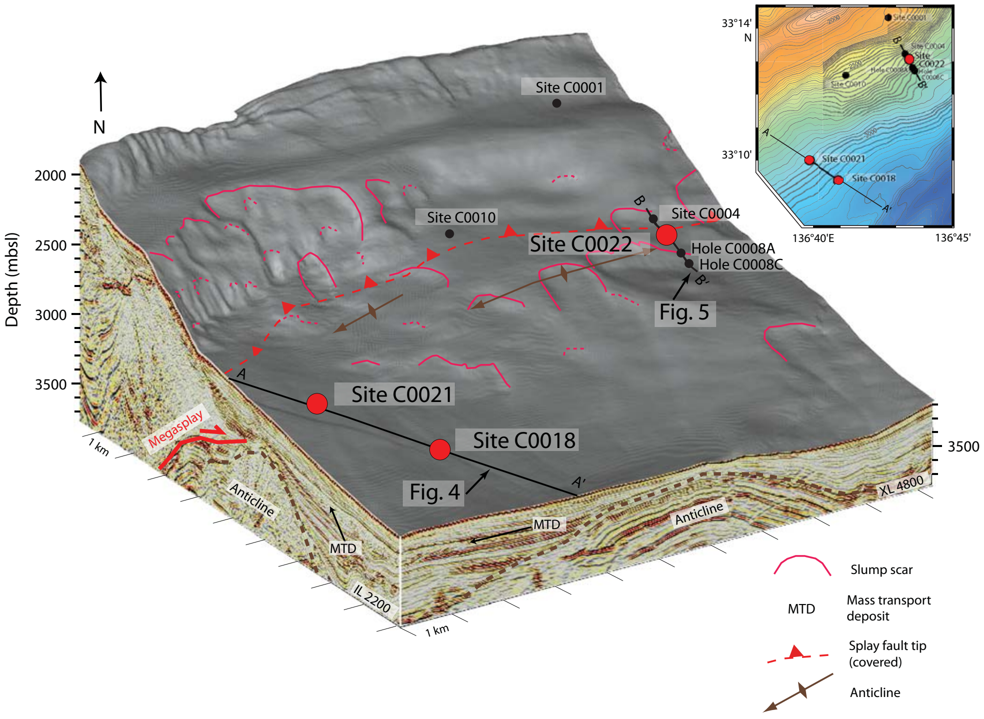

**Figure 3.** Detailed surface morphology and structure of the slope basin at the footwall of the splay fault (Strasser et al., 2011) showing Expedition 338 sites (red) in relation to NanTroSEIZE Stage 1 and 2 sites (black). Solid black lines = locations of seismic lines A–A′ and B–B′ in Figs. 4 and 5, respectively. MTD = mass transport deposit, IL = in-line, XL = cross-line.

Basin on the crest of Kashinosaki Knoll (Ike et al., 2008) on the subducting Philippine Sea Plate (Figs. 1, 2) to understand (1) how compressional velocity relates to compaction state and fluid sources; and (2) how igneous basement structures relate to the alteration state.

## 2.1 Site C0002 in Kumano forearc basin

Five lithologic units (I–V), based on cuttings and cores, are identified at Site C0002 (Fig. 6). In the Kumano forearc basin sediment (lithologic units II and III) in holes C0002J, C0002K, and C0002L, bedding is subhorizontal to gently dipping. At the base of lithologic Unit III, however, bedding is intensely disrupted and boudinaged. Vein structures (Ogawa, 1980) were observed in cores and cuttings exclusively from Unit III in holes C0002F and C0002J.

The lithologic Unit III/IV boundary is defined at different depths in holes C0002F and C0002J as a result of mixing of cuttings over an interval of as much as ~100 m in

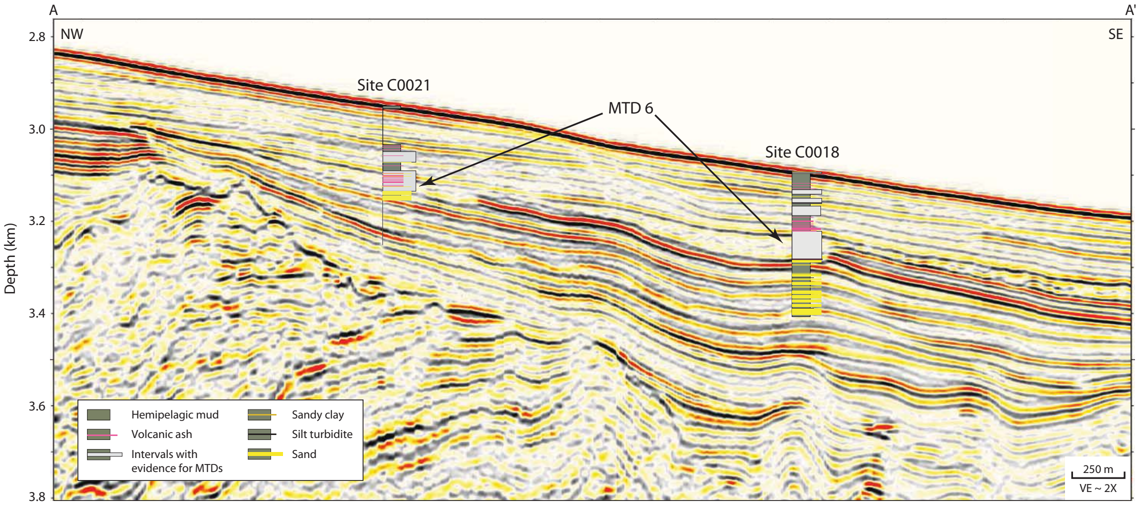

**Figure 4.** Lithostratigraphic summary columns of sites C0018 and C0021 overlain on an arbitrary seismic line A–A′ linking the two sites. Seismic line location shown in Fig. 3. MTD = mass transport deposit, VE = vertical exaggeration.

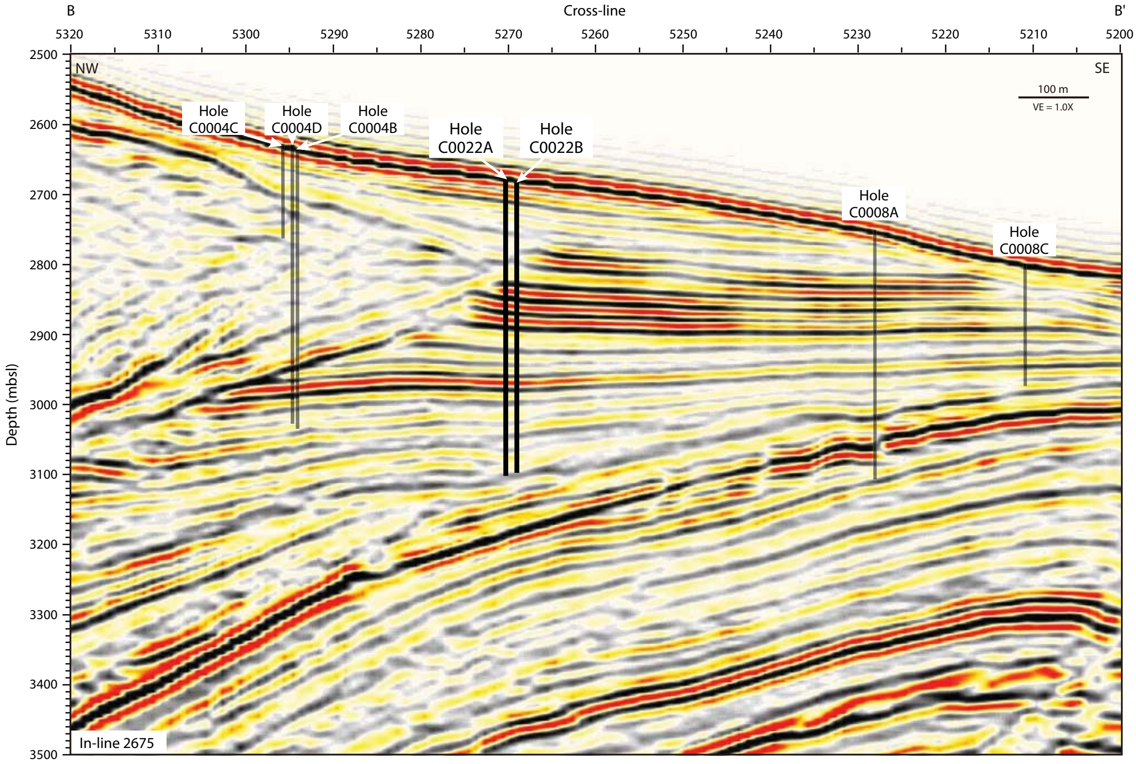

**Figure 5.** In-line 2675 (B–B′) extracted from 3-D seismic volume, showing sites C0004, C0008, and C0022 (Moore et al., 2009). Location shown in Fig. 3. VE = vertical exaggeration.

C0002F, resulting in uncertainty of that depth magnitude (see Strasser et al., 2014a for a detailed discussion of reaming while drilling and the mixing of cuttings). The lithologic Unit III/IV boundary was cored at 926.7 m b.s.f. in Hole C0002J (Fig. 6), where we interpret it as an erosional unconformity.

In the upper accretionary prism (lithologic Unit IV, holes C0002H and C0002J), bedding is subhorizontal to steeply dipping toward the south or north. Up to 10 % of the cuttings in the interval 1550.5–1675.5 m b.s.f. exhibit slickenlined surfaces. This interval correlates with the high fracture

**Table 1.** Expedition 338 coring summary.

| Hole | Latitude | Longitude | Water depth (m b.s.l.) | Cores (*N*) | Interval cored (m) | Core recovered (m) | Recovery (%) | Drilled interval (m) | Total penetration (m) | Time on site (days) |
|---|---|---|---|---|---|---|---|---|---|---|
| 338- | | | | | | | | | | |
| C0002F | 33°18.0507′ N | 136°38.2029′ E | 1939.00 | 0 | LWD/MWD | – | – | 842–2005.5 | 2005.5 | 6.2 |
| C0002H | 33°18.0252′ N | 136°38.2152′ E | 1936.50 | 2 | 19.0 | 3.91 | 20.6 | 0–1120.0 | 1120.0 | 3.5 |
| C0002I | 33°18.0362′ N | 136°38.2077′ E | 1936.00 | 0 | – | – | – | – | 1360.5 | 5 |
| C0002J | 33°18.0173′ N | 136°38.2312′ E | 1937.50 | 7 | 38.0 | 22.19 | 58.4 | 0–940.0 | 940.0 | 3.5 |
| C0002K | 33°18.0063′ N | 136°38.2103′ E | 1937.50 | 11 | 86.5 | 60.29 | 69.7 | 0–286.5 | 286.5 | 3 |
| C0002L | 33°17.9970′ N | 136°38.2200′ E | 1937.50 | 24 | 228.0 | 186.4 | 81.8 | 0–505.0 | 505.0 | 3 |
| | | Site C0002 totals: | | 44 | 371.5 | 272.79 | 73.4 | 0–2005.5 | 6217.5 | 80 |
| C0012H | 32°44.8783′ N | 136°55.0351′ E | 3509.50 | 0 | LWD/MWD | – | – | 0–710.0 | 710.0 | 6 |
| | | Site C0012 totals: | | 0 | – | – | – | 0–710.0 | 710.0 | 6 |
| C0018B | 33°09.4319′ N | 136°40.8826′ E | 3084.5 | 0 | LWD/MWD | – | – | 0–350 | 350.0 | 1.5 |
| | | Site C0018 totals: | | 0 | – | – | – | 0–350 | 350.0 | 1.5 |
| C0021A | 33°10.0482′ N | 136° 39.4854′ E | 2940.50 | 0 | LWD/MWD | – | – | 0–294.0 | 294.0 | 1 |
| C0021B | 33°10.0555′ N | 136°39.8610′ E | 2944.00 | 14 | 120.4 | 129.91 | 107.90 | 0–194.5 | 194.5 | 4 |
| | | Site C0021 totals: | | 14 | 120.4 | 129.91 | 107.90 | 0–294.0 | 488.5 | 5 |
| C0022A | 33°13.0680′ N | 136°43.4540′ E | 2675.50 | 0 | LWD/MWD | – | – | 0–420.5 | 420.5 | 3 |
| C0022B | 33°13.0833′ N | 136°43.4667′ E | 2674.00 | 41 | 345.0 | 305.5 | 88.6 | 0–419.5 | 419.5 | 6.5 |
| | | Site C0022 totals: | | 41 | 345.0 | 305.5 | 88.6 | 0–420.5 | 840.0 | 9.5 |
| | | Expedition 338 totals: | | 198 | 836.9 | 708.2 | 84.6 | | 8606.0 | 102 |

LWD = logging while drilling, MWD = measurement while drilling. – = not applicable.

concentration interval of 1500–1550 m b.s.f. and a fault identified at 1638 m b.s.f. on LWD resistivity images.

Salinity, chlorinity, and sodium in interstitial water show similar changes with depth, reaching minimum concentrations at 300–500 m b.s.f. (Fig. 7). These minimum concentrations are attributable to freshwater derived from the dissociation of methane hydrate.

Methane in headspace gas shows a relatively high concentration at ~ 300 m b.s.f., and propane shows high concentration from 200 to 400 m b.s.f. (Fig. 7). The methane- and propane-rich interval (200–400 m b.s.f.) corresponds to the gas hydrate zone inferred from resistivity and sonic log data (Expedition 314 Scientists, 2009). No massive gas hydrates were found in cores from this interval, although gas-rich sands were common. This suggests disseminated methane hydrate. A methane peak was observed in mud gas data at the Unit III/IV boundary.

The ratio of methane to ethane plus propane ($C_1/[C_2 + C_3]$) and $\delta^{13}C$ concentration in methane ($\delta^{13}C–CH_4$) suggest that the methane in the gas hydrate zone is mostly of microbial origin (Strasser et al., 2014a). The $C_1/(C_2 + C_3)$ and $\delta^{13}C–CH_4$ data of mud gas sampled during riser drilling in Hole C0002F show that thermogenic methane gradually increases with depth up to ~ 50 % at ~ 2000 m b.s.f.

Discrete moisture and density (MAD) data on cuttings (below 875.5 m b.s.f. in Hole C0002F) show lower bulk density and higher porosity compared with measurements on discrete samples from cores, as observed during previous riser drilling (Expedition 319 Scientists, 2010; Inagaki et al., 2012). Analyses of Expedition 338 cuttings revealed that these differences resulted from mixing of aggregates produced during the drilling process, termed drilling-induced cohesive aggregates.

Compressional borehole breakouts and drilling-induced tensile fractures (DITFs) observed in Hole C0002F suggest a northeast–southwest orientation of the maximum horizontal stress ($\sigma_{H_{\mathrm{max}}}$), which is consistent with breakout data obtained in Hole C0002A (Expedition 314 Scientists, 2009). A leak-off test (LOT) performed at 875.5 m b.s.f. yielded an estimate of 32 MPa as the least horizontal principal stress ($\sigma_{H_{\mathrm{min}}}$), which is consistent with a LOT performed at 703.9 m b.s.f. in Hole C0009A (Expedition 319 Scientists, 2010).

## 2.2 Sites C0018, C0021 and C0022 in the outer wedge

LWD logs (holes C0018B and C0021A) and cores (Hole C0021B) were collected to characterize MTDs in the slope basin seaward of the megasplay fault zone. New logging data are used to define two logging units in Hole C0018B (Fig. 8) and three subunits in Hole C0021A logs (Fig. 9), which correlate to subunits defined based on visual core descriptions and X-ray CT images in Hole C0021B (Fig. 9) and at Site C0018 (Expedition 333 Scientists, 2012a).

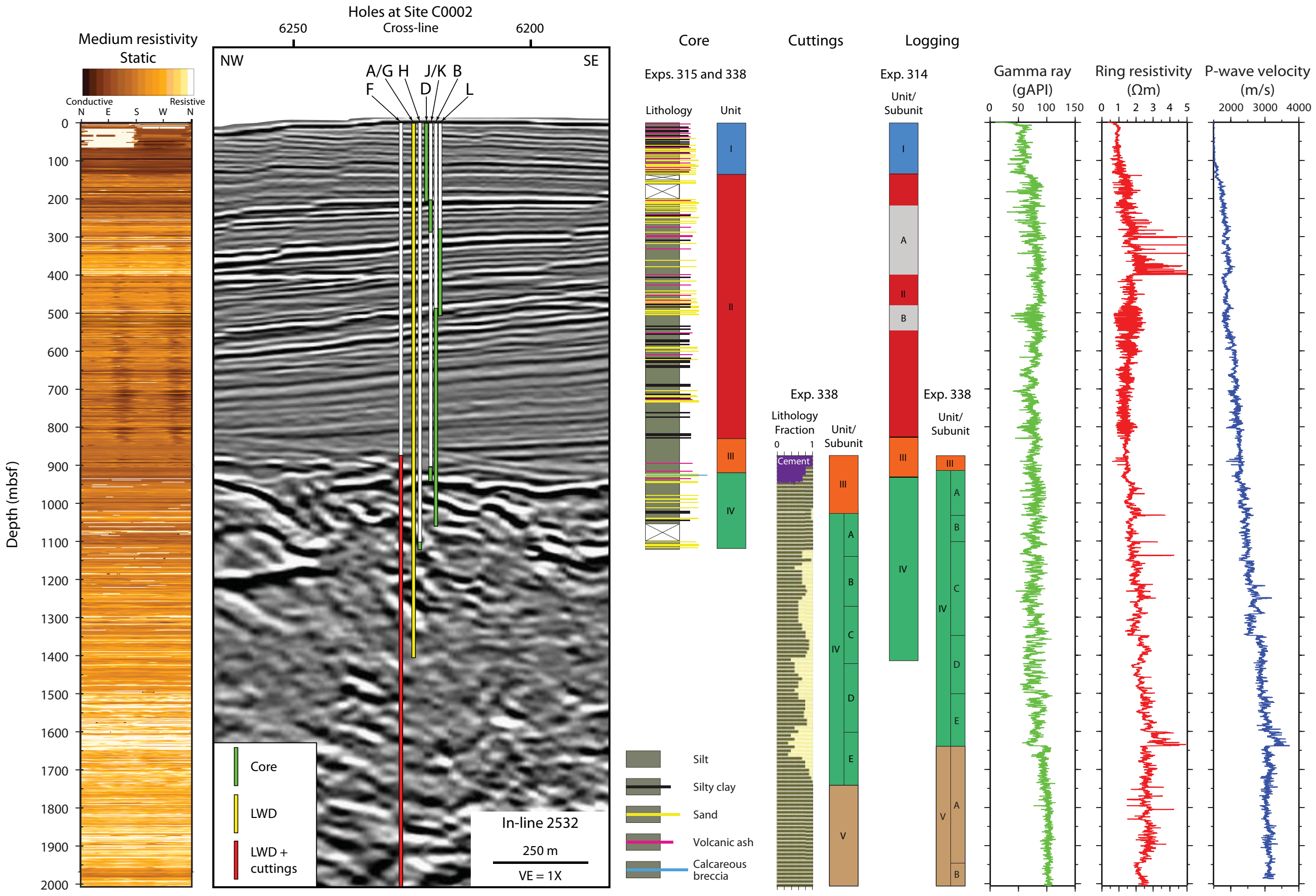

**Figure 6.** Cuttings-core-log-seismic integration at Site C0002: composite medium button static resistivity, In-line 2532 seismic data (Kumano 3-D PSDM volume; Moore et al., 2009), composite core lithology and units, cuttings lithology and units, logging units from holes C0002A and C0002F, and composite logging-while-drilling (LWD) data. In logging unit panel (Exp. 314), gray interval A indicates possible gas-hydrate zone, and interval B indicates possible area with small amounts of free gas (after Expedition 314 Scientists, 2009).

### 2.2.1 Site C0018

Six MTDs (1–6) were identified in cores from Hole C0018A (Expedition 333 Scientists, 2012a); however, the lower resolution of the LWD data allowed interpretation of only two MTD intervals in Hole C0018B by resistivity image analysis. The tadpole diagram (bedding dip angle in Fig. 8) shows the high-angle, randomly oriented bedding (Fig. 8). Logging MTD B corresponds to lithologic MTD 6 in cores from Hole C0018A, while the depth range of logging MTD A encompasses lithologic MTDs 3–5 of Hole C0018A (Fig. 8).

### 2.2.2 Site C0021

Lithologic Unit IA is composed of mottled silty clay with rare thin interbeds of fine sand and ash layers. Lithologic Unit IB is composed of a succession of thin sand beds interbedded with silty clay and occasional ash layers (Fig. 9). Unit IA also contains two intervals of MTD with chaotic and distorted bedding, i.e., MTD A and MTD B (Fig. 9). The top of MTDs A and B are defined by a zone of mud clasts capped by a thin draping sand. Below the mud clasts, a zone of chaotic/tilted/homogenous bedding occurs. The base of the MTDs is defined as the last occurrence of a shear zone, which also corresponds to the base of a zone with relatively high shear strength. We note that MTD A identified in Hole C0021B and the upper zone with chaotic bedding observed in Hole C0021A do not have the same characteristics as MTD A identified from structural analysis of the resistivity image data in Hole C0018B (Strasser et al., 2014b), which was postulated to correspond to several of the smaller MTDs observed in Hole C0018A cores (Strasser et al., 2014b; Expedition 333 Scientists, 2012a). The mismatch between the upper sections of these two sites is corroborated by the seismic data (Fig. 4), which show that the package of low reflectivity at the corresponding depth at Site C0021 is truncated to the southeast and does not extend to Site C0018.

A prominent regional seismic reflection (Kimura et al., 2011; Strasser et al., 2011) marks the top of the thickest MTD

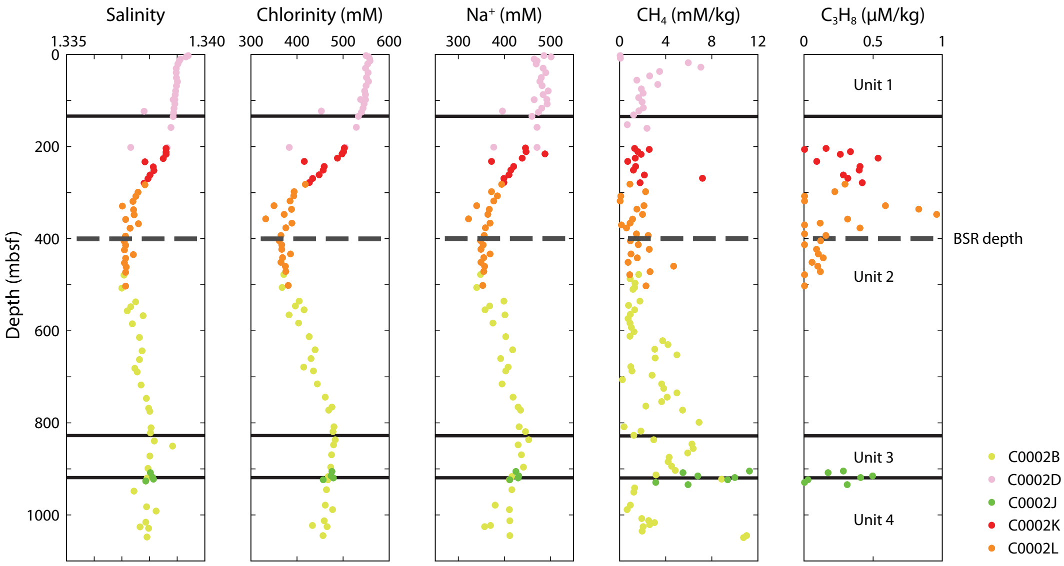

**Figure 7.** Profiles of salinity, chlorinity, and $Na^+$ in interstitial water, and those of methane and propane in headspace gas at Site C0002. Gray dashed line indicates level of BSR for reference. Lithologic unit boundaries are from core interpretations (after Expedition 315 Scientists, 2009; Strasser et al., 2014a).

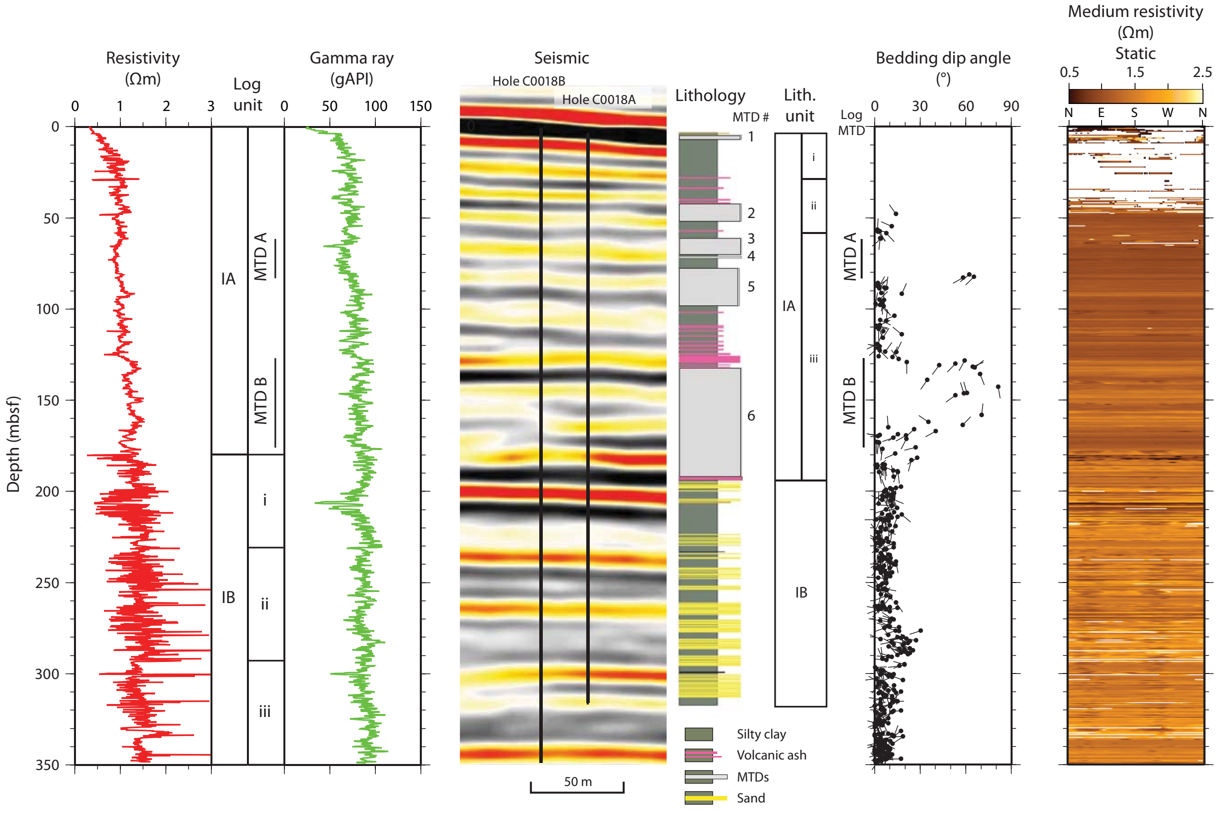

**Figure 8.** Core-log-seismic integration at Site C0018: LWD data, lithology with mass transport deposit (MTD) intervals and lithologic units, seismic data from In-line 2315 (Kumano 3-D PSDM volume; Moore et al., 2009), bedding dips, and medium button static resistivity.

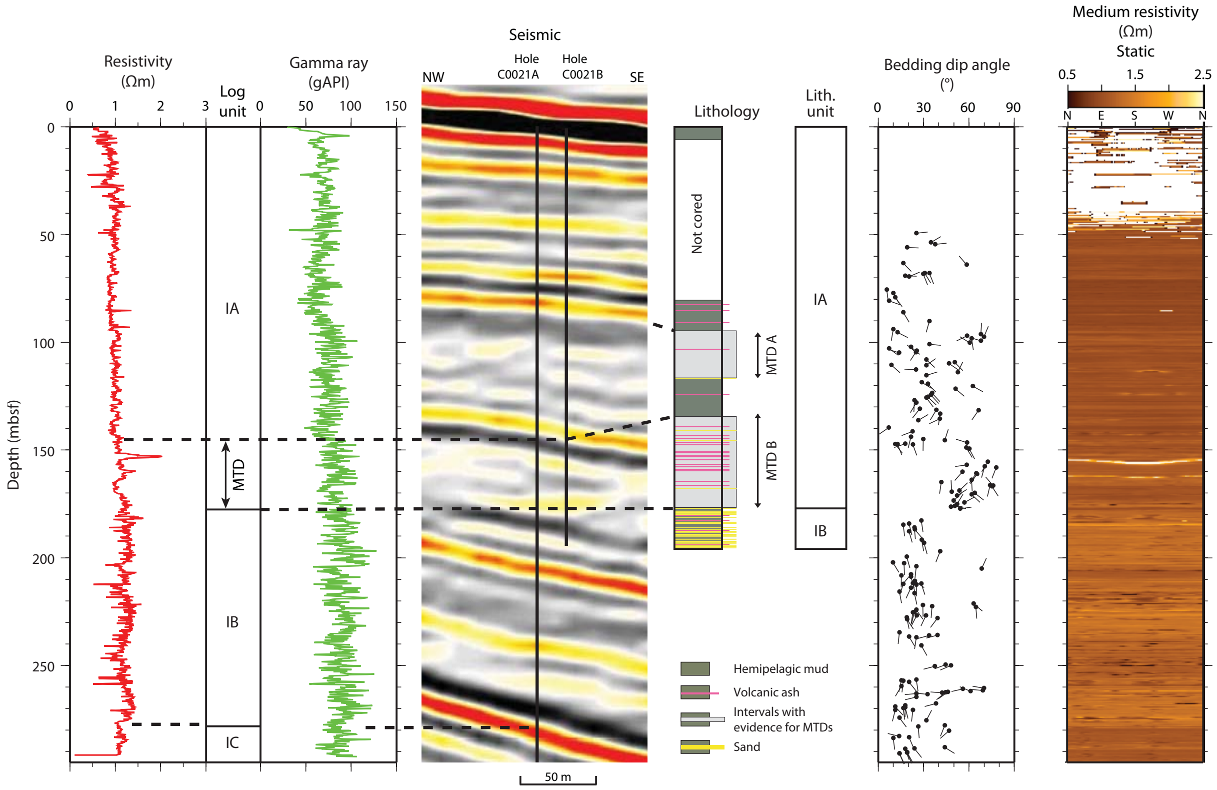

**Figure 9.** Core-log-seismic integration at Site C0021: LWD data, lithology with mass transport deposit (MTD) intervals and lithologic units, seismic data from In-line 2270 (Kumano 3-D PSDM volume; Moore et al., 2009), bedding dips, and medium button static resistivity.

(Fig. 4), which represents MTD 6 and MTD B at sites C0018 and C0021, respectively (Figs. 8, 9).

### 2.2.3 Site C0022

LWD data and cores were collected at Site C0022 to characterize the uppermost 400 m of sediment near the tip of the megasplay fault zone where the seaward-most branch of this fault system approaches the surface (Figs. 2, 5; Moore et al., 2007, 2009).

Two lithologic subunits are recognized in Hole C0022B. Subunit designations are adopted with minor modification from Site C0008 (Expedition 316 Scientists, 2009). Subunit IA is dominated by silty clay with a variable component of calcareous nannofossils, foraminifers, siliceous biogenic debris, and volcanic ash (Fig. 10). Subunit IB consists of a series of interbedded mud clast gravels with thin sand, clayey silt, and silty clay in the upper part and is dominated by silty clay in the lower part (Fig. 10). This mud clast gravel is correlative with a similar section at ~ 245–270 m b.s.f. in lithologic Subunit IB of Hole C0008A (Expedition 316 Scientists, 2009).

Bedding is subhorizontal with dip angles < 15° throughout the entire section, except in the vicinity of the possible splay fault.

The interval of 100–101 m b.s.f. (delineated by gray line, Fig. 10) is a plausible candidate for the location of the splay fault at Site C0022, because of: (1) increased bedding dip with systematic orientation; (2) more minor faults 20 m above this interval; (3) poor core recovery; and (4) three 2 cm-thick intervals of claystone showing planar fabrics not encountered elsewhere in Hole C0022B.

A high-resistivity (up to ~ 1.5 Ωm) interval at 85–88 m b.s.f., a low-resistivity (0.72 Ωm) spike at 100 m b.s.f., and a high-resistivity (up to ~ 1.7 Ωm) interval at 102–106 m b.s.f. correspond to a highly fractured zone and are likely related to the megasplay faulting (Fig. 10).

Interstitial water data in Hole C0022B are similar to those in holes C0004D, C0008A, and C0008D. However, the depth profiles of pH, chlorinity, $Na^+$, $Ca^{2+}$, $Fe^{2+}$, $Li^+$ and $Rb^+$ change at ~ 100 m b.s.f., perhaps associated with the megasplay fault.

MAD measurements show that porosity decreases from 70 % at the seafloor to 45–50 % at ~ 100 m b.s.f. and then increases to 60 % at 150 m b.s.f. The minimum porosity occurs at 93.4–94.7 m b.s.f., which is close to the proposed location of the megasplay fault.

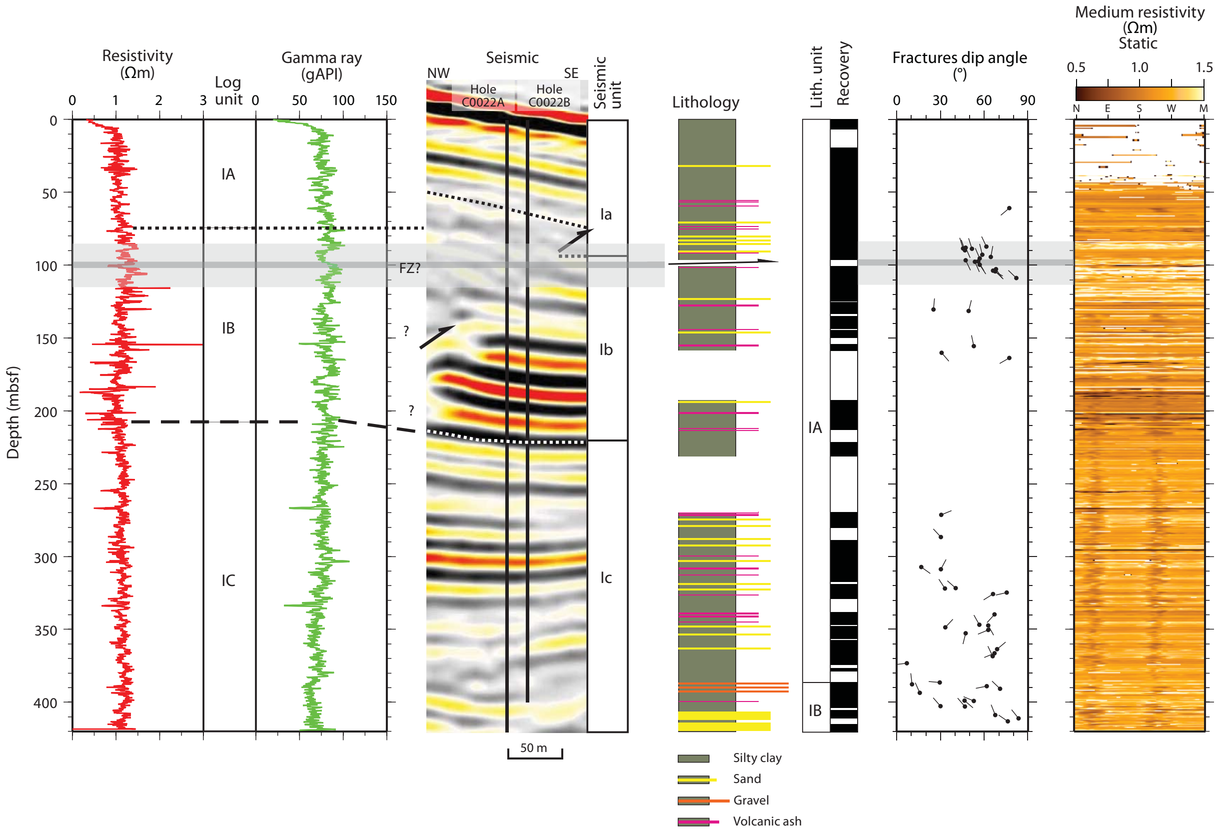

**Figure 10.** Core-log-seismic integration at Site C0022: LWD data and seismic data from In-line 2315 (Kumano 3-D PSDM volume; Moore et al., 2009) with seismic units defined by Kimura et al. (2011), lithology and lithologic units, fracture dips, and medium button static resistivity. Dashed and dotted black lines show correlations ("?" = tentative) between the different data sets. Shaded box highlights tip of the splay fault zone (FZ) and wider deformation zone, identified from fractures in resistivity images and shear zones in cores.

## 2.3 Site C0012 on Kashinosaki Knoll

LWD data in Hole C0012H (0 to 709.0 m b.s.f.) can be combined with core analyses from previous expeditions (Expedition 322 Scientists, 2010; Expedition 333 Scientists, 2012b) and seismic data (Park et al., 2008) to characterize the subduction zone inputs.

Based on variations of the gamma ray data, eight logging units were identified: six (I–VI) within the sedimentary cover and two (VII and VIII) within the basement, which are mostly comparable to lithologic units identified by Expedition 322 Scientists (2010) and Expedition 333 Scientists (2012b) (Fig. 11). Logging units IV, VI and VII were further divided into subunits based on resistivity and sonic velocity.

Logging Unit VII (530.3–626.6 m b.s.f.) represents the uppermost part of the oceanic basement, and corresponds to lithologic Unit VII and seismic Unit G (Fig. 11). Through logging Unit VII, the resistivity, *P* wave velocity and gamma ray logs exhibit significant variations, with jumps to high resistivity and gamma ray values in subunit VIIB (Fig. 11), possibly reflecting variable sediment volume within the basement or variable alteration of the basalt.

Logging Unit VIII (626.6–709 m b.s.f.) is characterized by low gamma ray values with minor fluctuations, high resistivity values and *P* wave velocities of ~ 4–5 km s$^{-1}$, suggesting the presence of uniform or fresh basalt (Fig. 11).

## 3 Summary

Riser drilling was conducted in Hole C0002F to 2005.5 m b.s.f. and suspended for future reoccupation and completion of the NanTroSEIZE project. LWD data, mud-gas analyses, and cuttings samples in Hole C0002F provided constraints on lithology, structure, physical properties, and geochemistry of the previously unaccessed deeper part of the Nankai accretionary prism. Riserless coring in holes C0002H, C0002J, C0002K, and C0002L provided core samples (1) across the previously unsampled gas hydrate zone of the Kumano forearc basin; (2) across the Kumano forearc basin – accretionary prism unconformity, and (3) in the uppermost accretionary prism. Thus, these operations enabled not only exploration of the accretionary prism to ~ 2005 m b.s.f., but also complemented current knowledge of Site C0002.

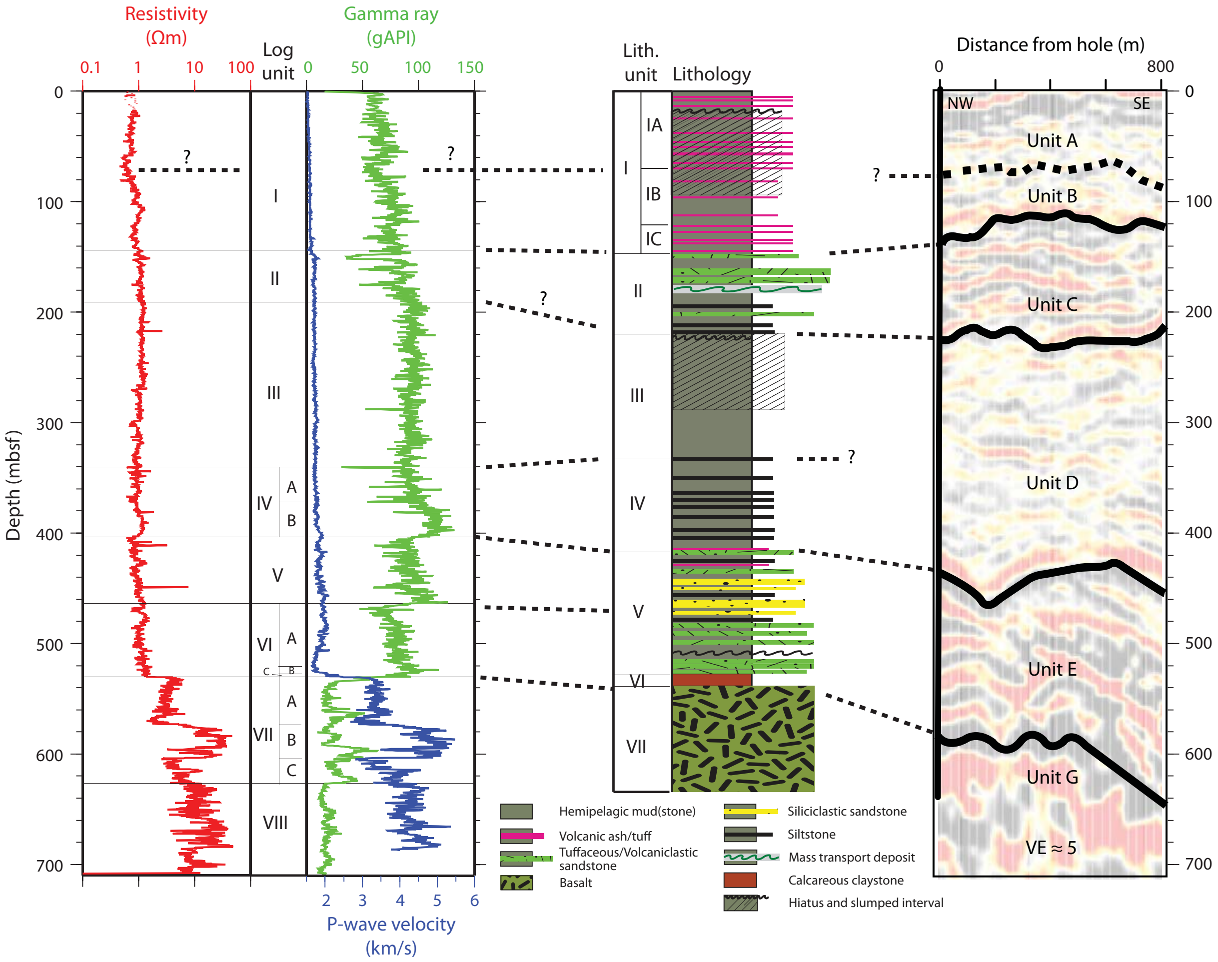

**Figure 11.** Core-log-seismic integration at Site C0012: LWD data from Hole C0012H with unit boundaries, composite lithologic column (holes C0012A–C0012G; Expedition 333 Scientists, 2012b), and seismic data from In-line 95 (IFREE 3-D PSDM volume; Park et al., 2008) showing the interpretation of Expedition 322 Scientists (2010). Black dashed lines = correlations ("?" = tentative) between unit boundaries identified for each data set. VE = vertical exaggeration.

LWD at sites C0012 and C0018 provided petrophysical data to complement coring from expeditions 322 and 333. Integration of existing core and 3-D seismic data with new LWD data enabled us to characterize the petrophysical, lithological and structural manifestation of the oceanic basement and its overlying sediment at a subduction input site (Site C0012) as well as submarine landslide dynamics and MTD emplacement processes at a Nankai Trough Submarine Landslide History (NanTroSLIDE) site (Site C0018).

LWD and coring at Site C0021 provided further information on the nature, provenance, and kinematics of the MTDs observed at Site C0018 and provided data on the lateral heterogeneity of MTDs.

LWD and coring at Site C0022 provided logging data and samples across the tip of the megasplay fault, which provided additional information on the activity of the megasplay fault and its bearing on earthquakes and tsunamis.

## The IODP Expedition 338 Scientific Party

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# IODP Expedition 336: initiation of long-term coupled microbiological, geochemical, and hydrological experimentation within the seafloor at North Pond, western flank of the Mid-Atlantic Ridge

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**Abstract.** Integrated Ocean Drilling Program (IODP) Expedition 336 addressed questions concerning subseafloor microbial life and its relation to seawater circulation and basalt–seawater reactions in the basaltic ocean crust. Sediment and basement samples were recovered at three drill sites located in the North Pond area, an 8 × 15 km large sediment pond on the 8 Ma western flank of the Mid-Atlantic Ridge around 22°45′ N and 46°05′ W in roughly 4450 m water depth. The average core recovery rate in basement was approx. 31 %. The subseafloor depth of the basement holes ranges from 90 to 332 m; sediment thickness is between 36 and 90 m. Two of the holes (U1382A, and U1383C) were equipped with advanced Circulation Obviation Retrofit Kit (CORK) observatories, employing – for the first time – fiberglass casing. Another CORK string was deployed in Deep Sea Drilling Project (DSDP) Hole 395A, but the wellhead broke off upon final installment. Nonetheless, the North Pond observatory is fully operational and post-cruise observatory research is already underway. Combined geochemical and microbiological studies of the drill core samples and experimental CORK materials will help understand (1) the extent and activity of microbial life in basalt and its relation to basalt alteration by circulating seawater, and (2) the mechanism of microbial inoculation of an isolated sediment pond.

## 1 Introduction

The upper ocean crust constitutes a permeable and hydrologically active aquifer holding as much as 1–2 % of the ocean's water (e.g., Fisher, 2005). Seawater circulation within this volcanic crust is well documented, but the extent to which microbes colonize, alter, and evolve in subsurface rock is essentially not known (e.g., Edwards et al., 2012a). It is well known that the geochemical changes associated with basalt alteration in the uppermost oceanic crust play an important role in setting ocean chemistry. Microbial habitats may be developed where the intensity of seawater–rock interaction is high. The role of microorganisms in this seawater–ocean crust exchange is currently unknown. Earlier studies of basement rocks from ocean drilling provided putative textural and isotopic indications of microbial life within the crust (e.g., Fisk et al., 1998; Staudigel et al., 2008). At the EPR 9N, rich and diverse bacterial life was found on young surface, lava flows (Santelli et al., 2008), but subseafloor samples yielded lesser extents of colonization (Santelli et al., 2010). Seafloor observatories provide a promising technique for in situ studies of microbial activity within ridge flank aquifers because they enable analysis of pristine formation fluids and experimental colonization devices, as has been previously demonstrated at the Juan de Fuca Ridge flank system (Cowen et al., 2003; Orcutt et al., 2010; Edwards et al., 2012b).

Expedition 336 was executed to address fundamental microbiological questions concerning the nature of the subseafloor deep biosphere in oceanic hydrological, geological, and biogeochemical contexts. Determining the nature of

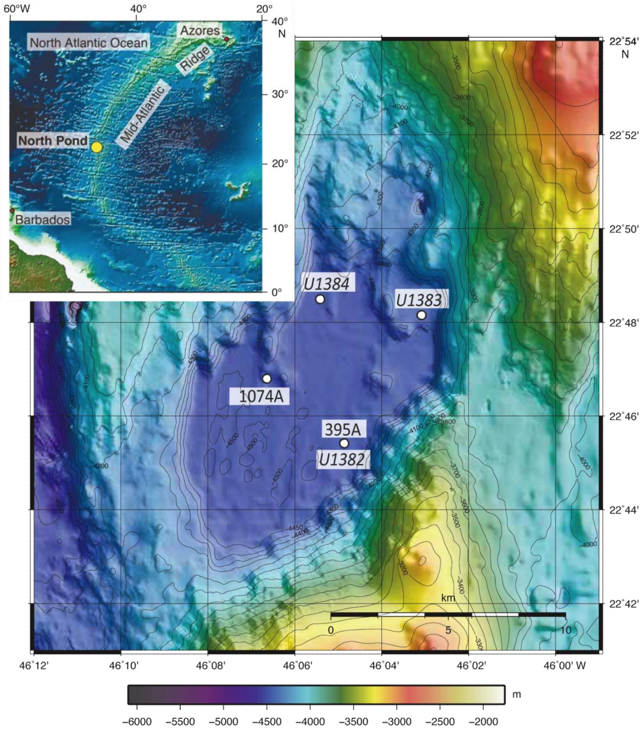

**Figure 1.** Bathymetric map of the North Pond area (data from Schmidt-Schierhorn et al., 2012) on the western flank of the Mid-Atlantic Ridge (see inset).

subseafloor microbiological communities in young igneous ocean crust and their role in ocean crust alteration was a primary objective. Specifically, we wanted to test the hypothesis that microbes play an active role in ocean crust alteration, while also exploring broad-based ecological questions such as how hydrological structure and geochemistry influence microbial community structures. We also intended to study the biogeography and dispersal of microbial life in subseafloor sediments.

## 2 Geological setting

All sites are located in the North Pond area at 22°45′ N, 46°05′ W in 4414 to 4483 m water depth (Fig. 1). From previous ocean drilling and site survey investigation, this 8×15 km basin was known as a site of particularly vigorous circulation of seawater in permeable 8 Ma basaltic basement underlying a < 300 m thick sedimentary pile. Heat flow surveys indicate that recharge occurs dominantly in the southeastern part of basin, which is consistent with basement fluid flow generally directed to the northwest (Langseth et al., 1992).

Deep Sea Drilling Project (DSDP) Leg 45 rotary core barrel (RCB) cored two holes at Site 395 (Fig. 1), revealing a 93 m-thick sediment sequence, consisting of 89 m of foraminifer-nannofossil ooze underlain by 4 m of calcareous brown clays with manganese micronodules (Melson et al., 1978). Basement penetration was 91.7 m (Hole 395) and 576.5 m (Hole 395A); a re-entry cone and casing to basement were installed in Hole 395A. The basement lithology is dominated by several units of massive and pillow lava flows, typically several 10s of meters in thickness, which are separated by sedimentary breccia (Bartetzko et al., 2001; Melson et al., 1978). A several meters thick peridotite–gabbro complex with brecciated contacts was cored in Hole 395 (Melson et al., 1978).

During several return missions to Hole 395A, logging operations, packer testing, and borehole fluid sampling were conducted (e.g., Becker et al., 1998). Temperature and flow logs indicated rapid fluid flow (~ 1000 L h$^{-1}$) down into Hole 395A and low formation pressures. Comparison of lithologic and downhole electrical resistivity logs for Hole 395A suggested a series of discreet basalt flows (i.e., different volcanic flow units with distinct geochemical and petrographic characteristics; Bartetzko et al., 2001). Most of the seawater recharge in Hole 395A is accommodated by aquifers tied to flow contacts within the uppermost 300 m of basement. Below that depth, temperature increases (Becker et al., 1998), and borehole fluid chemistry indicates significant chemical exchange with the rocks in the borehole walls (Gieskes and Magenheim, 1992).

During IODP Leg 174B, Hole 1074A was cored near the northwestern margin of North Pond (Fig. 1). Temperature and geochemical profiles are diffusive, indicating there is no upward advection of basement fluids through the sediments, even in an area of local high heat flow (Becker et al., 1998). This observation is consistent with the hydrologic model of Langseth et al. (1992) that indicates fluid flow is predominantly lateral beneath all of North Pond, and recharge/discharge is taking place through basement outcrops that surround the basin.

## 3 Science and operational objectives

The primary operational goal for Expedition 336 was installations of subseafloor borehole observatories for long-term coupled microbiological, geochemical, and hydrological experiments. The observatories were designed to allow monitoring conditions and study processes in situ after the drilling-induced disturbance and contamination of the borehole environment have dissipated. Sampling of basement and sediment for microbiological and geochemical studies was conducted on cores retrieved from the CORK holes and their immediate vicinity.

A specific goal was to drill a basement hole to > 500 meters below seafloor (m b.s.f.) at a site in the northern area of presumed fluid discharge. We had also planned on drilling a basement hole to ~ 175 m b.s.f. and ~ 70 m into the basaltic crust in another area in the northern part of the sediment pond. For both sites, downhole hydrologic (packer) tests and wire-line logging were planned, but installation of

**Table 1.** Overview of operational achievements.

| Site | 395 | U1382 | | U1383 | | | | | U1384 |
|---|---|---|---|---|---|---|---|---|---|
| Hole | 395A | U1382A | U1382B | U1383A | U1383B | U1383C | U1383D | U1383E | U1384A |
| Latitude (N) | 22°45.3519′ | 22°45.3531′ | 22°45.3528′ | 22°48.1229′ | 22°48.1328′ | 22°48.1241′ | 22°48.1316′ | 22°48.1283′ | 22°48.7086′ |
| Longitude (W) | 46°04.8609′ | 46°04.8911′ | 46°04.8748′ | 46°03.1661′ | 46°03.1556′ | 46°03.1662′ | 46°03.1628′ | 46°03.1582′ | 46°05.3464′ |
| Seafloor depth (m b.r.f.) | 4484.0 | 4494.0 | 4494.0 | 4425.2 | 4425.2 | 4425.2 | 4425.2 | 4425.2 | 4475.9 |
| Interval cored | 0.0 | 100.0 | 98.8 | 0.0 | 0.0 | 262.0 | 44.3 | 44.2 | 96.2 |
| Length recovered | 0.00 | 31.79 | 84.28 | 0.00 | 0.00 | 50.31 | 48.65 | 50.28 | 94.09 |
| Percent recovered | – | 32 % | 85 % | – | – | 19 % | 110 % | 114 % | 98 % |
| Section drilled w/o coring | 0.0 | 110.0 | 0.0 | 36.0 | 89.8 | 69.5 | 0.0 | 0.0 | 0.0 |
| Total penetration | 0.0 | 210.0 | 98.8 | 36.0 | 89.8 | 331.5 | 44.3 | 44.2 | 96.2 |
| Total depth of hole | 5084.0 | 4704.0 | 4592.8 | 4461.2 | 4515.0 | 4756.7 | 4469.5 | 4469.4 | 4572.1 |
| Operations conducted | Retrieved Leg 174 CORK, logged, installed CORK (failed wellhead) | Cored basement, logged, installed CORK | Cored sediment and basement contact | Jet-in test | Installed cone and casing; bit lost in hole, 35 m open hole, ROV platform deployed | Cored basement, logged, installed CORK | Cored sediment and basement contact | Cored sediment and basement contact | Cored sediment and basement contact |

CORK observatories was the primary objective in order to conduct experiments in the uppermost basement hydrological environment. A third goal was to recover the existing first-generation CORK at Hole 395A in the SE corner of the pond and install a multi-level subseafloor observatory there. Advanced piston coring (APC) of the $< 90$ m sediment covers in the different areas was another objective. Enhanced education and outreach programs were intended to communicate the excitement and importance of scientific drilling and exploration to a broad audience, build educational curricula, and create media products (photographic, sound, video, and web based) that help achieve critical outreach goals.

Our science objectives for Expedition 336 were to recover sediment and basement and establish subseafloor basement observatories to address two major scientific questions:

1. What is the nature of microbial communities harbored in young ridge flanks and what is their role in ocean crust weathering? What role do microorganisms play on a global basis in promoting seafloor weathering? What energy sources do the microorganisms utilize? How different are communities in different zones in the subseafloor that are characterized by different fluid fluxes and temperature? Geochemical data indicate that oxidative seafloor alteration occurs mostly during the first 10–20 Ma of crustal age, and thereafter slows or even ceases. These records suggest that the most reasonable place to search for active subcrustal microbial communities should be in young, cold ridge flank environments. Chemical reaction kinetics are inhibited at low temperatures, providing a window of opportunity for biological catalysts to take advantage. Yet, the extent and activity of microbial life in these settings remains undetermined. Also, the extent of direct participation in alteration by extant communities in the subseafloor is not clear.

2. Where do deep-seated microbial communities come from? Were they derived from overlying bottom seawater, which acts as a steady source of inoculum that seeds microorganisms (particle-attached and free-living) to sediments? Or is the microbial inoculum provided by advective transport from the basement (passive transport) or by lateral active transport (swimming) from adjacent, older sediments following redox gradients? North Pond was considered an ideal location to test these opposing hypotheses, which have important mechanistic implications concerning dispersal in the deep biosphere, and evolutionary consequences for microbial life on earth.

The low heat flow ridge flank at North Pond represents an ideal model system for studying biologically mediated oxidative basement alteration via the use of CORKed microbial observatories. The work will also provide an excellent point of comparison for the studies taking place at the Juan de Fuca Ridge, which represent the warm, sedimented endmember in the global spectrum of ridge flanks.

## 4 Expedition summary

Expedition 336 successfully initiated subseafloor observatory science at a young mid-ocean ridge flank setting. A summary of the operational achievements is presented in Table 1. Basement was cored and wire-line-logged in Holes U1382A and U1383C. Upper oceanic crust in Hole 1382A, which is only 50 m west of DSDP Hole 395A, was cored between 110 and 210 m b.s.f.; 31 % of the penetrated basement was recovered, producing different volcanic flow units with distinct geochemical and petrographic characteristics (Fig. 2).

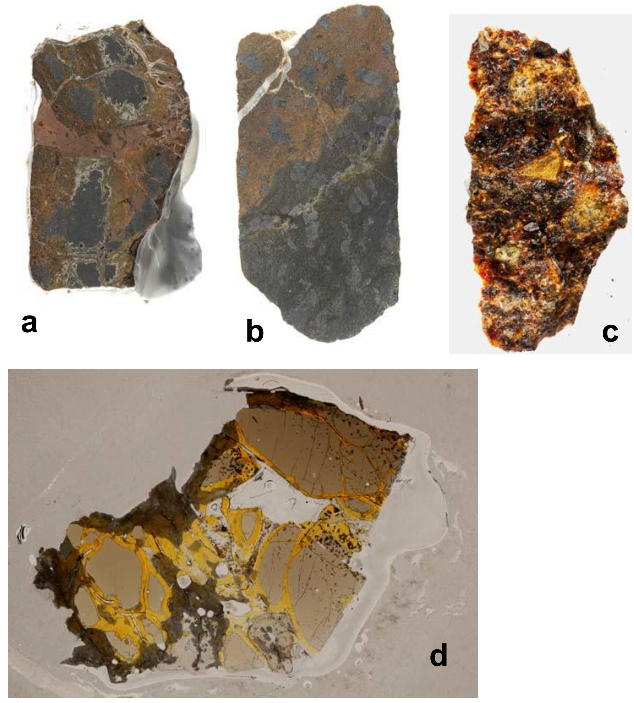

**Figure 2.** **(a)** Photograph of sample U1382A-5R-1, 116–119 cm, a strongly altered hyaloclastite (length of piece: 3 cm). **(b)** Photograph of sample U1382A-8R-4, 50–63 cm, a strongly serpentinized mantle peridotite with an oxidation halo along a prominent aragonite vein (length of piece: 13 cm). **(c)** Photograph of sample U1383C-17R-1, 120–123 cm, a strongly altered hyaloclastite dedicated for microbiological studies (length of piece: 3 cm) **(d)** Thin section photomicrograph (Sample U1383C-20R-1, 111–113 cm) showing glassy to spherulitic fragments of a hyaloclastite with pronounced palagonite rims (brown) and zeolite (colorless) filling void space. Width of image is 1.2 cm.

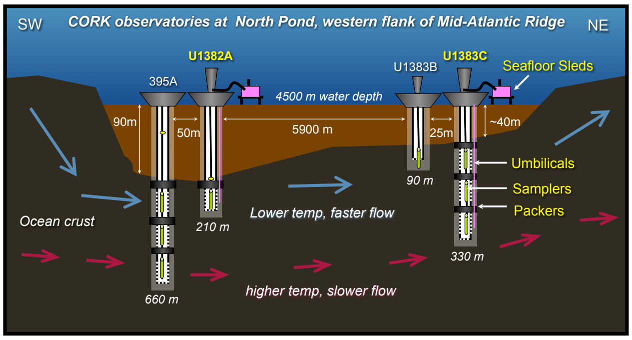

**Figure 3.** Simplified sketch of the geological and hydrological framework and the observatory layout at North Pond. Two observatories (U1382A ad U1383C; large wellhead) are fully operational and sampling/experimentation using seafloor sleds (Cowen et al., 2012) and incubation chambers (FLOCs; Orcutt et al., 2011). In Hole U1383B, a CORK-lite (small wellhead) was installed using a remotely operated vehicle (Wheat et al., 2012). Flow lines of formation water are highly schematic and adapted from Langseth et al. (1992).

Intercalated between two flow units is a sedimentary breccia, containing clasts of basalt, gabbroic rocks, and mantle peridotite; this unit was interpreted as a rockslide deposit. Hole 1383C recovered 50.3 m of core from an interval between 69.5 and 331.5 m b.s.f. (Fig. 2). The basalts are aphyric to highly plagioclase–olivine-phyric tholeiites that fall on a liquid line of descent controlled by olivine fractionation. They are fresh to moderately altered, with clay minerals (saponite, nontronite, celadonite), Fe oxyhydroxide, carbonate, and zeolite as secondary phases replacing glass and olivine to variable extents. Sediment thickness was about 90 m at Sites 1382 and 1384 and varied between 38 and 52 m at Site 1383. The sediments are predominantly nannofossil ooze with layers of coarse foraminiferal sand and occasional sand- to pebble-sized clasts of basalt, serpentinite, gabbroic rocks, and bivalve debris. The lowermost meters of the APC-cored sections feature brown clay at Sites 1382 and 1384. XCB-coring at the sediment–basement interface recovered < 1 m of brecciated basalt with micritic limestone at all three sites. XCB cores from Hole 1382B also contained ultramafic clasts, suggesting that the uppermost meters of basement at Site 1382 may be talus rather than lava flow. Sediments were intensely sampled for geochemical pore water analyses and microbiological work. Shipboard determination of dissolved oxygen concentrations in the pore waters indicate pronounced C-shaped profiles, indicating diffusion of oxygen into the sedimentary pile from both the water–sediment and sediment–basement interfaces and oxygen consumption by aerobic microbial activity within the sediments (Orcutt et al., 2013).

Expedition 336 installed fully functional observatories in two newly drilled holes (U1382A and U1383C). The principle layout of the observatory as of May 2012 is depicted in Fig. 3. The CORK wellhead at Hole 395A broke off, and another Hole (U1383B) was abandoned after a bit failure. Hole 1383B was penetrated 89 m into the seafloor and is equipped with a re-entry cone and remotely operated vehicle (ROV) landing platform for future observatory science objectives. This hole has, in the meantime, been equipped with a Miniature-CORK that was installed during a joint US–German cruise in April/May of 2012 (Wheat et al., 2012). Details of the CORK observatory layout and installation are reported in Edwards et al. (2012c). In principle, the observatories consist of sensors for temperature, pressure, oxygen concentration and osmotically driven fluid sampling and microbial incubation devices. Fluid sampling lines run down to packer-sealed compartments in the subseafloor and allow post-drilling sampling using ROVs. During a first ROV cruise in April/May of 2012, first fluid samples were collected and osmo-samplers as well as other instrument packages (GeoMicrobe sleds; Cowen et al., 2012) were deployed. A repeat visit was recently conducted (April, 2014), and the overall duration of the CORK experiment is 6–8 yr. The

CORK observatory in Hole U1382A has a packer seal in the bottom of the casing and monitors/samples a single zone in uppermost oceanic crust extending from 90 to 210 m b.s.f. Hole U1383C was equipped with a three-level CORK observatory that separates a zone of thin basalt flows with intercalated limestone (56–142 m b.s.f.) from one within glassy, thin basaltic flows and hyaloclastites (142–196 m b.s.f.) and a lowermost zone (196–331.5 m b.s.f.) of more massive pillow flows with occasional hyaloclastite in the upper part. The instrument strings are inside fiberglass casing, which, unlike the traditional steel casings, are noncorrosive and hence will not produce hydrogen upon reaction with borehole water – a critical achievement for subseafloor microbiologic and geochemical experiments. The use of fiberglass casing is a novel development in the history of scientific ocean drilling and one of the operational highlights of the expedition.

Major strides in ridge flank studies have been made by employing CORK subseafloor observatories, as they facilitate combined hydrological, geochemical, and microbiological studies and controlled experimentation within the subseafloor. The North Pond observatory is representative of young and cold ridge flanks and complements similar observatories on the eastern flank of the Juan de Fuca Ridge. These observatories will help constrain the importance of ridge flanks as microbial habitats and the role of seawater circulation in crust–ocean transfers of heat and matter.

## The IODP Expedition 336 Scientific Party

Members of the the IODP Expedition 336 Scientific Party included Louise Anderson, Nicolas Backert, Keir Becker, Dale W. Griffin, Amanda G. Haddad, Yumiko Harigane, Hisako Hirayama, Samuel M. Hulme, Steffen Leth Jørgensen, Tania Lado Insua, Paul Le Campion, Heath J. Mills, Kentaro Nakamura, Beth Orcutt, Young-Soo Park, Victoria Rennie, Olivier Rouxel, Joseph A. Russel, Kasumi Sakata, Everett C. Salas, Fengping Wang, and C. Geoffrey Wheat

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Scientific Drilling
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# The SCOPSCO drilling project recovers more than 1.2 million years of history from Lake Ohrid

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**Abstract.** The Scientific Collaboration on Past Speciation Conditions in Lake Ohrid (SCOPSCO) project is an international research initiative to study the influence of major geological and environmental events on the biological evolution of lake taxa. SCOPSCO drilling campaigns were carried out in 2011 and 2013. In 2011 we used gravity and piston coring at one of the five proposed drill sites, and in 2013 we undertook deep drilling with the Deep Lake Drilling System (DLDS) of Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC). In April and May 2013, a total of 2100 m sediments were recovered from four drill sites with water depths ranging from 125 to 260 m. The maximum drill depth was 569 m below the lake floor in the centre of the lake. By retrieving overlapping sediment sequences, 95 % of the sediment succession was recovered. Initial data from borehole logging, core logging and geochemical measurements indicate that the sediment succession covers > 1.2 million years (Ma) in a quasi-continuous sequence. These early findings suggest that the record from Lake Ohrid will substantially improve the knowledge of long-term environmental change and short-term geological events in the northeastern Mediterranean region, which forms the basis for improving understanding of the influence of major geological and environmental events on the biological evolution of endemic species.

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## 1 Introduction and goals

The Scientific Collaboration on Past Speciation Conditions in Lake Ohrid (SCOPSCO) project is an international research initiative to study the influence of major geological and environmental events on the biological evolution of aquatic taxa. The target site is Lake Ohrid, considered the oldest lake in continuous existence in Europe, and which contains more than 200 endemic species. The recovery of long sediment sequences from Lake Ohrid enables us to obtain information about the age and origin of the lake, and helps to improve our understanding of the regional climatic and environmental evolution including the history of Italian volcanic eruptions.

Lake Ohrid is $\sim$ 30 km long, 15 km wide, covers an area of 358 km$^2$, and is located at an altitude of 693 m above sea level (a.s.l.) between Albania and Macedonia on the Balkan Peninsula (Fig. 1). The lake has a maximum water depth of 289 m and a volume of 55.4 km$^3$. The total inflow of water can be estimated to 37.9 m$^3$ s$^{-1}$, with ca. 25 % originating from direct precipitation and 25 % from riverine inflow. About 50 % of the total inflow derives from karst aquifers, of which ca. 8 m$^3$ s$^{-1}$ are believed to come from Lake Prespa (Wagner et al., 2010, and references therein). Including Lake Prespa, the total catchment covers an area of 2393 km$^2$. Evaporation (40 %) and the main outflow, the river Crni Drim (60 %), balance the water budget of Lake Ohrid. Due to its large water volume and low nutrient availability, Lake Ohrid is highly oligotrophic today (e.g. Wagner et al., 2010). The surface water has a specific conductivity of $\sim$ 200 µS cm$^{-1}$ and a pH of $\sim$ 8.4 (Matter et al., 2010).

Lake Ohrid is renowned for having an outstanding degree of biodiversity for several groups of organisms, including 212 described endemic species. Endemic species are found in several groups, including bacteria, macrophytes, diatoms, and almost all animal groups such as crustacea, molluscs and fish (Albrecht and Wilke, 2008). There are very few lakes worldwide that contain species with this degree of endemism; examples include lakes Baikal, Tanganyika, Victoria and Malawi. However, all these lakes have a much larger surface area, meaning that Lake Ohrid is the most diverse lake in the world when the number of endemic species is related to surface area (Albrecht and Wilke, 2008). This intriguing characteristic contributed significantly to the establishment of Lake Ohrid as UNESCO World Heritage Site in 1979.

Lake Ohrid is considered to be the oldest lake in Europe and is one of the very few ancient lakes on earth that has likely existed continuously for more than 1 Ma. Geological studies suggest that the lake basin formed during the final phases of Alpine orogeny in an approximately N–S trending graben structure between ca. 10 and 2 Ma (cf. Lindhorst et al., 2014). Molecular clock analyses of several endemic species flocks (i.e. groups of closely related species) indicate that Lake Ohrid is probably 1.5 to 3 Ma old (Trajanovski et al., 2010).

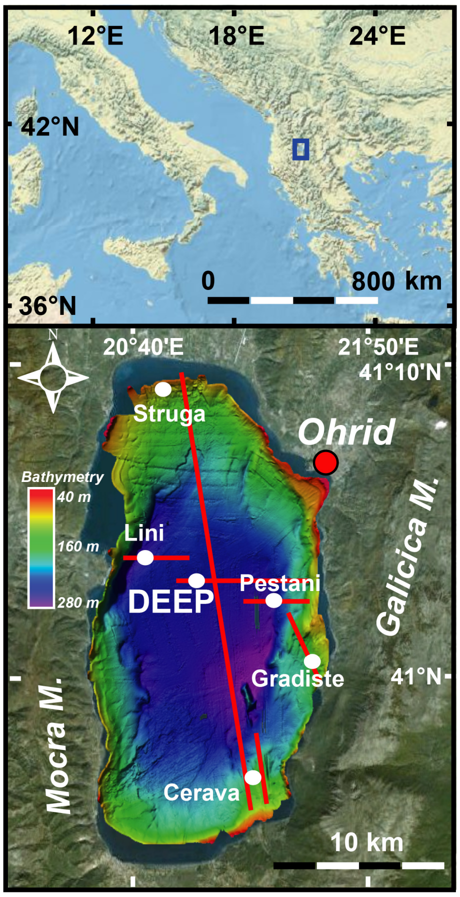

**Figure 1.** Topographic and bathymetric map of Lake Ohrid on the Balkan Peninsula. ICDP coring sites are indicated by white dots. The red lines indicate the locations of seismic profiles shown in Figs. 2, 3 and 4.

Previous sedimentary records from Lake Ohrid are up to ca. 15 m long and span the last glacial/interglacial cycle with some minor hiatuses. These records indicate that Lake Ohrid sediments contain information on long- and short-term climate change in this region (e.g. Vogel et al., 2010a; Wagner and Wilke, 2011). Other terrestrial records spanning more than 1 Ma are rare from the northern Mediterranean region. The most prominent study is likely the pollen record from Tenaghi Philippon, which covers the last ca. 1.35 Ma (Tzedakis et al., 2006). Continuous marine records of equivalent age are also rare and often analysed at too low temporal resolution (e.g. Kroon et al., 1998) to reliably reconstruct short-term events. In addition to generating proxy data on long- and short-term environmental change, our preliminary studies also revealed that Lake Ohrid is a distal archive of the activity of Italian volcanoes. Its sediments comprise ca. 10 tephra and cryptotephra (i.e. non-visible tephra) layers in the last ca. 140 ka. These volcanic event

**Table 1.** SCOPSCO drill sites.

| Site | Water depth (m) | # of holes (planned) | Total drill metres (m) | Total recovery (m) | Deepest drill depth (m b.l.f.) | Length of composite record * (m) | Remarks |
|---|---|---|---|---|---|---|---|
| DEEP | 243 | 6 (2) | 2088.71 | 1526.06 | 568.92 | 544.88 (95.77 %) | spot coring |
| Cerava | 119/131 | 2 (2) | 175.71 | 172.20 | 90.48 | 87.86 (97.10 %) | site on a slope |
| Gradište | 131 | 3 (2) | 327.35 | 224.46 | 123.41 | 114.07 (92.43 %) | |
| Peštani | 262 | 1 (0) | 194.50 | 177.90 | 194.50 | 177.90 (91.45 %) | |
| Lini | 260 | 1 (2) | 10.08 | 10.08 | 10.08 | 10.08 (100.00 %) | drilled in 2011 |
| Struga | 0 | 0 (2) | 0 | 0 | 0 | 0 | skipped |

* Composite field recovery is estimated based on field depths and magnetic susceptibility measurements.

layers provide information on ash dispersal from the prominent volcanic regions in Italy and contribute significantly to the construction of a robust chronology by comparison with other dated records in the region using tephrochronological cross-correlation of geochemical fingerprints (Sulpizio et al., 2010; Caron et al., 2010; Vogel et al., 2010b; Damaschke et al., 2013). In addition, analysis of Lake Ohrid sediments will generate information on tectonic events. The lake is located in a highly active seismic zone with frequent earthquakes (e.g. Muço et al., 2002; NEIC database, USGS), and the lacustrine sediments on the subaquatic slopes are subject to mass wasting and seismite formation (Wagner et al., 2008; Reicherter et al., 2011; Lindhorst et al., 2012). Studies from other lakes and marine basins have shown that these mass-wasting deposits can be used to reconstruct the long-term earthquake history of a region (e.g. Schnellmann et al., 2002; Beck et al., 2012).

Despite uncertainties in age estimation, its likely continuous existence over more than 1 Ma makes Lake Ohrid an extant hotspot of evolution and an evolutionary reservoir enabling relict species to survive (Albrecht and Wilke, 2008). These outstanding characteristics allowed Lake Ohrid to become one of the target sites within the scope of the International Continental Scientific Drilling Program (ICDP). The deep drilling of Lake Ohrid has four major aims: (i) to obtain precise information about the age and origin of the lake, (ii) to unravel the regional seismotectonic history including effects of major earthquakes and associated mass-wasting events, (iii) to obtain a continuous record containing information on Quaternary volcanic activity and climate change in the central northern Mediterranean region, and (iv) to evaluate the influence of major geological events on evolution and the generation of the observed extraordinary degree of endemic biodiversity.

## 2 Site selection

The site selection for the deep drilling project was based on hydro-acoustic surveys carried out between 2004 and 2008. Multichannel seismic data were collected using a Mini GI Air Gun (0.25 L in 2007 and 0.1 L in 2008) and a 16-channel 100 m long streamer, complemented by parametric sediment echosounder profiles (SES-96 light in 2004 and SES 2000 compact in 2007 and 2008, Innomar Co.). The theoretical vertical resolution of both types of seismic data can be estimated to be 2 m for the Mini GI gun and 0.2 m for the Innomar data.

Based on a dense grid of multichannel seismic data (~ 500 km total length) and sediment echosounder profiles (> 900 km total length), five drill sites were originally proposed (Fig. 1; Table 1). They range from 80 to 260 m water depth and had target drilling depths between 20 and 680 m.

The "DEEP" site is located in the central basin of Lake Ohrid in ~ 250 m water depth. This master site is well suited to address most of our key research questions (Table 1). The seismic data from the central basin show a rough basement topography with numerous highs and lows (Figs. 2 and 3). The basement lows are characterized by onlap fills and therefore suggested possible recovery of the longest records. The DEEP site is located in a basement depression with an estimated maximum sediment fill of 680 m (Fig. 3). Seismic data show undisturbed sediments without unconformities or erosional features, thus suggesting that a continuous sediment record of maximum age and free of major hiatuses could be recovered. Strong multiples, however, mask the lower part of the sedimentary succession.

The "Struga" site is located close to the northern shore of Lake Ohrid (Fig. 1). It is the shallowest (80 m water depth) of all the sites. The objectives of this site are to investigate changes in the hydrological regime, to obtain information on lake level fluctuations, and potentially to obtain macrofossils for a cross-validation with the results obtained from molecular clock analyses. The intention to drill at the Struga site in the northern part of the lake was abandoned for logistical reasons during the drilling campaign. Instead, a new site was selected in the eastern part of the lake. This "Peštani" site (Fig. 1) had a water depth of 260 m and was chosen with the aim of reaching sediments deposited directly above the bedrock at ca. 200 m below lake floor (b.l.f.; Fig. 4).

The "Cerava" site (Figs. 1 and 4) is located on a lake terrace in 125 m water depth close to the southern shore of Lake Ohrid, 2–3 km off the southern feeder spring area and Cerava River, which are the main tributaries to Lake Ohrid. Several

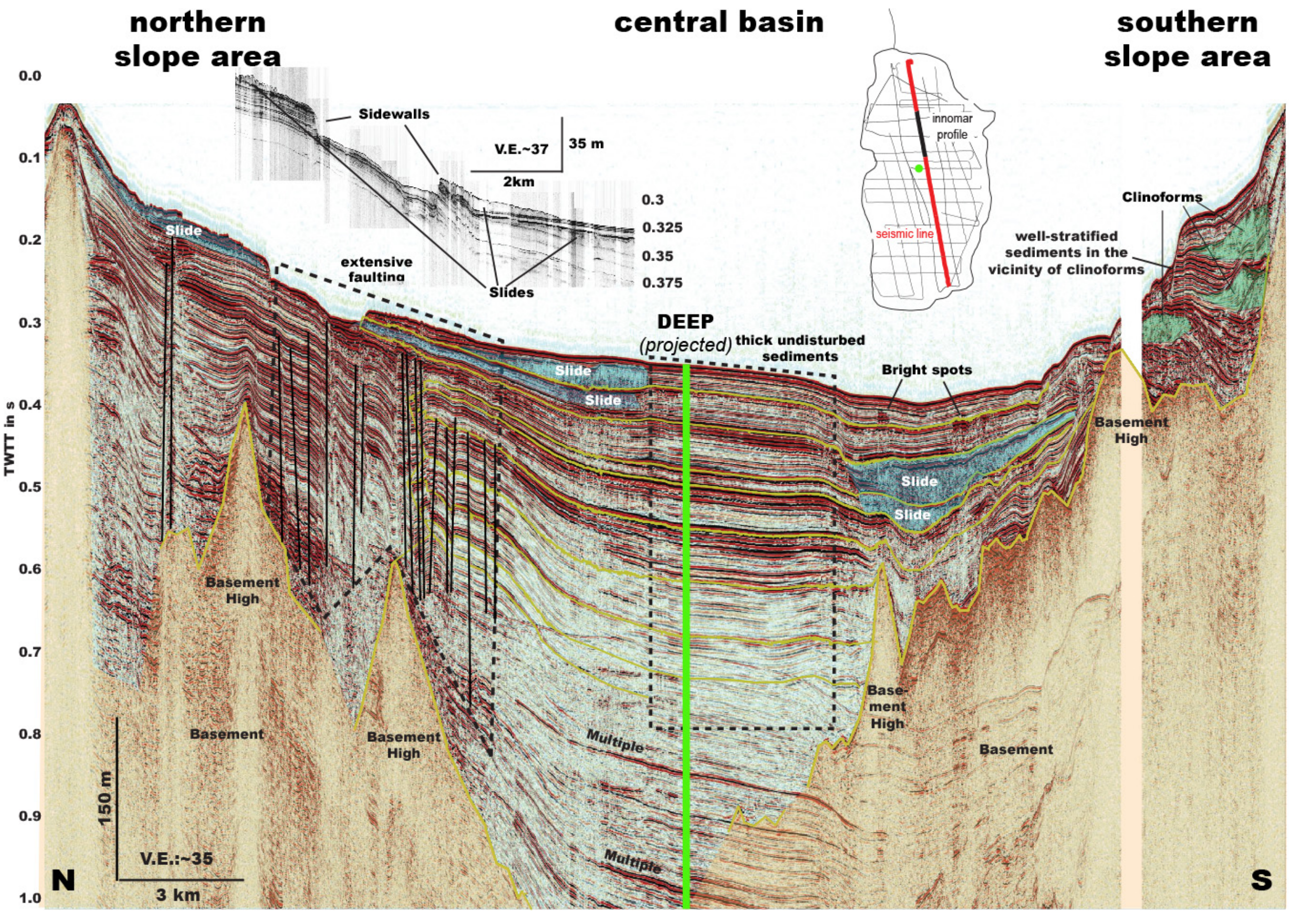

**Figure 2.** Seismic profile crossing Lake Ohrid in N–S direction. The central basin shows thick undisturbed sediments, which were drilled at the DEEP site. The DEEP site is about 1 km to the west of the seismic line. Other prominent features include faults, slides, clinoforms and bright spots. See Fig. 1 for location.

clinoforms in the seismic data reflect the development of terraces, which are linked to lake-level fluctuations. The main objective of this site is to reconstruct these variations. In addition, data from this core will be used to support our interpretation of tectonic activities and related mass-movement events.

The "Gradište" site (Figs. 1 and 4) is located in 130 m water depth close to the eastern margin of the lake in the hanging wall of a major active lake-bounding normal fault. The bathymetry reveals a steep west-dipping major fault associated with a small graben on the lake floor, which suggests recent activity of this fault. The Gradište site is also characterized by high inflow from sublacustrine karstic springs and constitutes the most important hotspot of endemic biodiversity in the lake. Macrofossils from this site are expected to best reflect the evolutionary history of invertebrates and plants and should allow us to test the role of sublacustrine springs in generating and maintaining biodiversity.

The "Lini" site (Figs. 1 and 4) is off the Lini Peninsula in 260 m water depth close to the western shore of Lake Ohrid. This locality was selected to study fault activity on the western basin bounding faults. Seismic profiles across the western coast show that the steepest gradient in front of the Lini Peninsula is due to active scarps of eastwards-dipping normal faults. The tectonic setting is comparable to the Gradište site with a set of active antithetic faults.

## 3 Coring results and borehole logging

Coring was originally planned for summer 2011 using Drilling, Observation and Sampling of the Earth's Continental Crust's (DOSECC) Deep Lake Drilling System (DLDS). Although this was postponed, a coring campaign using UWITEC (Austria) equipment was carried out in June 2011 in order to recover a 20 m long sediment sequence proposed for the Lini site and also surface sediment cores from the DEEP site. A gravity corer was used to obtain the undisturbed surface sediments, and deeper sediments were recovered with a piston corer. A re-entry cone, which was positioned on the lake bed, and extension rods of 2 m length controlled the exact release of the piston to ensure retrieval of a

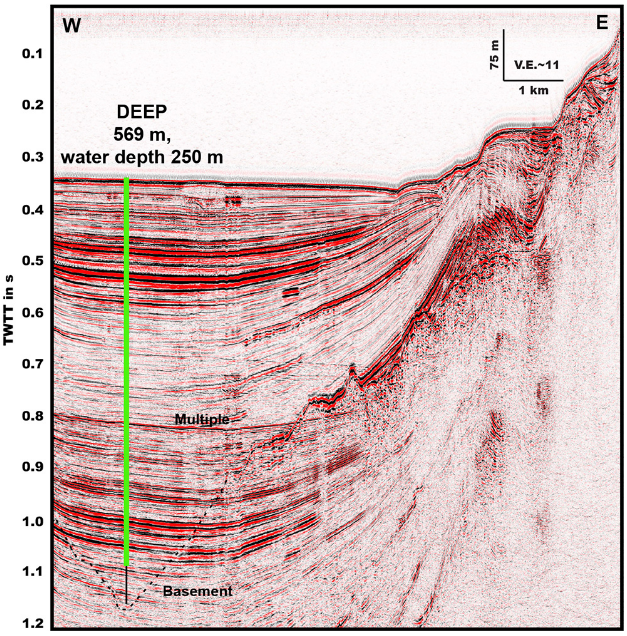

**Figure 3.** Seismic profile crossing the DEEP site in W–E direction (only Macedonian part of Lake Ohrid due to missing Albanian permissions during the 2007 survey). See Fig. 1 for location. The green line in the seismic profile indicates the approximate maximum depth of cores recovered from DEEP site, whilst the black line indicates the originally proposed target depth.

continuous core sequence. Core recovery at the Lini site was around 100 % including core catcher samples. Core loss or disturbance of sediment between the individual 2 m segments is therefore regarded as low (< 6 cm). However, bad weather and high waves on Lake Ohrid stopped the coring campaign at ca. 10 m depth in 2011. At the DEEP site, a 1.6 m long surface sediment sequence was retrieved.

A fire on the container vessel MV *MSC Flaminia*, which transported the DLDS from the US to Europe in summer 2012, caused a second delay for the start of the drilling operations. Finally, drilling started in late March 2013, and by late May 2013 a total of ~ 2100 m of sediment had been recovered from Lake Ohrid at four different sites. The SCOPSCO drilling operation is heralded as one of the most successful ICDP lake drilling campaigns ever.

At the DEEP site, six parallel holes were drilled with a maximum sediment depth of 569 m b.l.f. (Fig. 3). Pelagic sediments characterize the uppermost 430 m of the sediment column (Fig. 5). Below 430 m b.l.f., shallow water facies became increasingly dominant, including fine-grained material with high organic matter content, coarser sediments with shell remains, and distinct sand layers. Gravel and pebbles hampered penetration deeper than 569 m b.l.f. In total, 1526 m of sediment cores were recovered from the six parallel holes at the "DEEP" site. Taking into account sediment–core overlap, the total composite field recovery amounts to 95 % (545 m), being higher (99 %) for the uppermost 430 m (Fig. 5). At the Cerava site, two parallel cores were drilled with a maximum sediment depth of 90.5 m b.l.f. (Fig. 6). The composite field recovery was ca. 97 % (88 m). The basal sediments recovered consist of lithified sediments and shell fragments or whole shells. At the Gradište site, three parallel cores were drilled with a maximum sediment depth of 123 m b.l.f. (Fig. 6). The composite core recovery was 92 % (114 m). Coarse-grained sediments dominate below 82 m b.l.f. At the Peštani site only one hole with a maximum sediment depth of 194.5 m b.l.f. was recovered (Fig. 6). The core recovery was 91 % (178 m).

At all four drill sites, generation of high-quality continuous downhole logging data comprising spectral gamma ray, magnetic susceptibility (MS), resistivity, dipmeter, borehole televiewer and sonic data was achieved. Additional zero-offset vertical seismic profiling was conducted at the DEEP site. Spectral gamma ray was run through the drill pipe, and thereafter pipes were pulled gradually to maintain the borehole stability. All the other tools were run in about 40 m long open hole sections.

## 4 Preliminary scientific results

### 4.1 Downhole logging

Downhole logging data at the DEEP site reveal contrasting physical properties in spectral gamma ray (gamma ray, $K$, $U$, Th), MS, resistivity and seismic velocity ($vp$) data. The sediment sequence below 430 m b.l.f. is characterized by higher gamma ray values (mean: 70 gAPI) than pelagic sediments above, showing a cyclic alternation of low (20 gAPI) and high (65 gAPI) gamma ray values (Fig. 5).

### 4.2 Sedimentological work

In addition to borehole logging, some data have already been generated from the sediment sequences recovered. The age model and sediment stratigraphy of the 10 m long sediment sequence recovered from the Lini site in summer 2011 spans the Late Pleistocene to Holocene and contains two mass-wasting deposits (Wagner et al., 2012). The more significant uppermost mass-wasting deposit is almost 2 m thick and directly overlies the AD 472/512 tephra. The exact age of this mass-wasting deposit cannot be defined because the tephras from AD 472 and AD 512 indicate geochemical overlapping, and the sediments of Lake Ohrid are not annually laminated. However, the lack of any apparent erosional discordance at the base of the mass-wasting deposit and the small distance to the AD 472/512 tephra imply that the mass-wasting deposit occurred in the early 6th century AD (Wagner et al., 2012). A likely trigger for this mass-wasting event could be a historical earthquake that destroyed the city of Lychnidus (Ohrid). According to historical documents, this earthquake could have occurred at AD 518, AD 526, or AD 527.

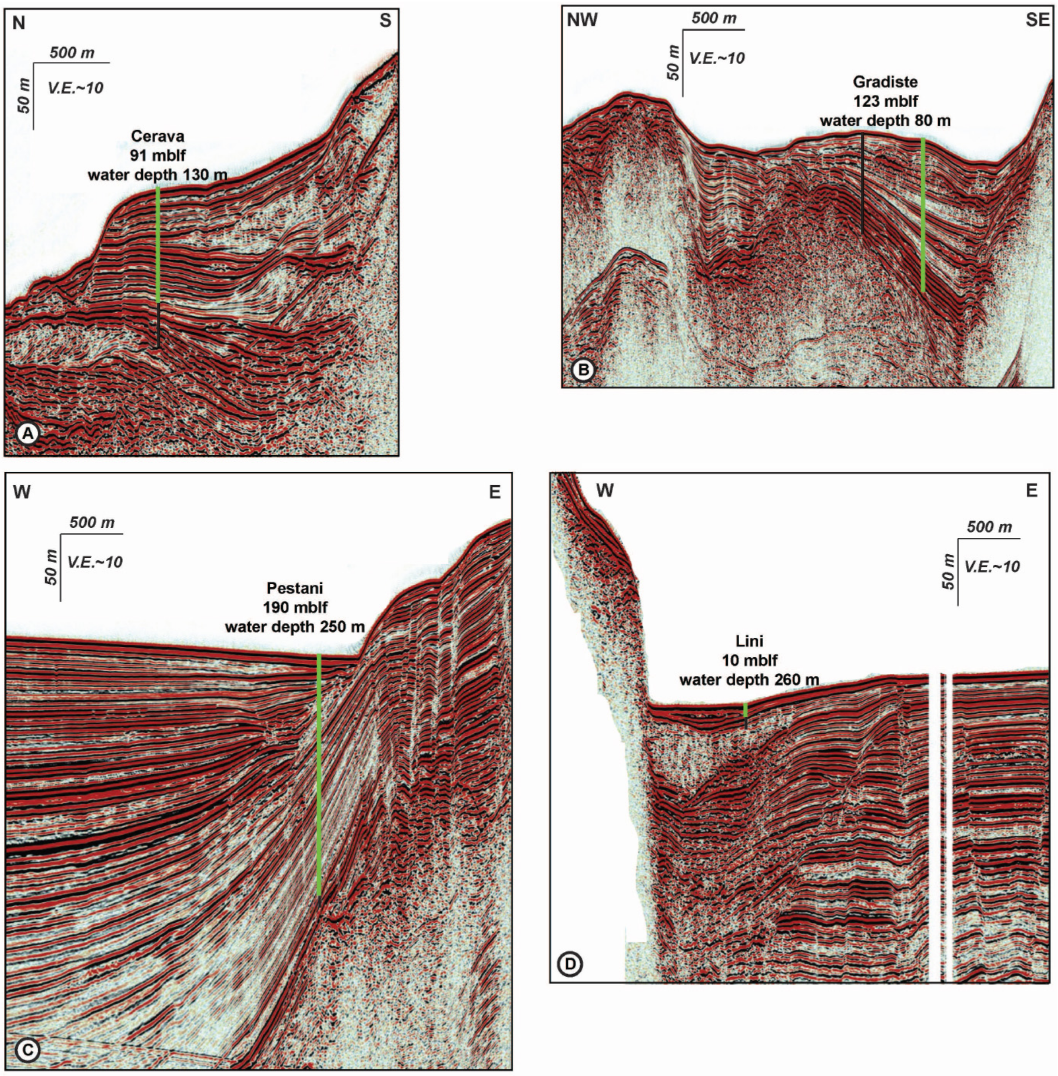

**Figure 4.** Seismic cross sections at drill sites **(A)** Cerava, **(B)** Gradište, **(C)** Peštani, and **(D)** Lini. The green line in the individual seismic profiles indicates the approximate maximum depth of cores recovered, whilst the black line indicates the target depth.

Although the sediment sequence from the Lini site is shorter than proposed, the results indicate that one of the main scientific goals of the project – to reconstruct active tectonics and mass wasting (Table 1) – can be achieved.

MS was measured on all cores recovered in summer 2013 using a multi-sensor core logger (MSCL; Geotek, UK) in a field laboratory. Logging started immediately after the transportation of the cores from the drilling platform to the laboratory in order to ensure best possible overlap between individual holes. The volume-specific MS was measured over 10 s for every 2 cm of each core section with a whole core loop sensor (internal diameter: 10 cm). The data show a pronounced cyclic pattern most likely related to glacial/interglacial cycles and demonstrate the excellent potential of Lake Ohrid for palaeoenvironmental reconstructions (Fig. 5). We also identified a similar cyclic pattern in the seismic data and interpreted them as a climatic signal (Lindhorst et al., 2014). A preliminarily correlation between seismic and MS data using a simple time–depth chart constructed out of available *p* wave velocity data for the DEEP site allows an optical correlation between the cyclicity of seismic and MS data (Fig. 5), demonstrating the great potential to integrate physical properties, sedimentological and seismic data. Distinct peaks of MS are most likely correlated with the occurrence of tephras or cryptotephras in the sedimentary succession.

Small aliquots of core catcher material from the DEEP site were freeze-dried and homogenized. This material was used for measurements of total carbon (TC) and total inorganic carbon (TIC) using a DIMATOC 200 (DIMATEC Co.). Total organic carbon (TOC) was calculated as the difference between TC and TIC. Studies of the sediment cores recovered

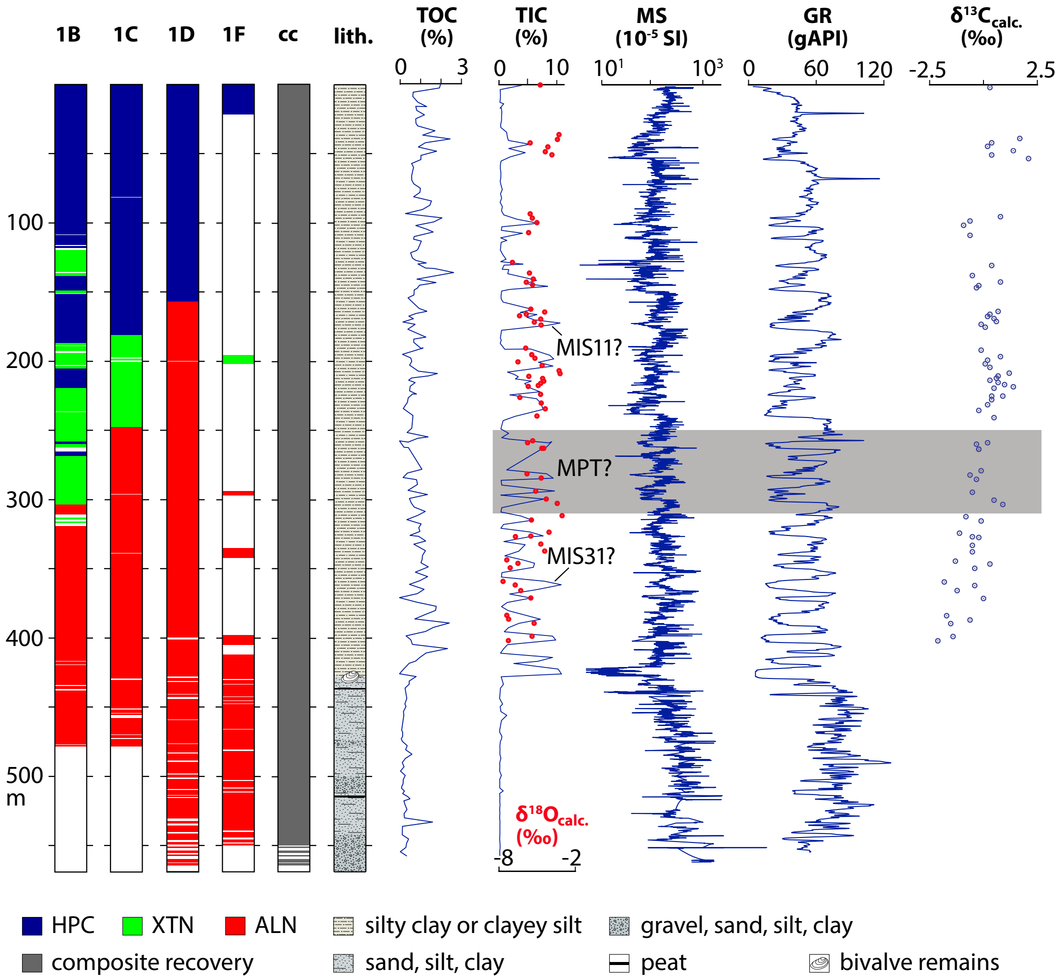

**Figure 5.** Core recovery and lithology from DEEP site. Colours indicate the different coring tools used for the four parallel holes 1B, 1C, 1D, and 1F with deeper penetration. A hydraulic piston corer (HPC, blue) was used for the recovery of the upper sediment sequences. The relatively soft consistency of these sediments allows penetration of a 3 m long piston corer by hydraulic pressure. Rotation drill tools were used for the deeper and more consolidated sediments and comprise the extended nose (XTN, green), where the drill bits stand back by about 12 cm from the core barrel front, and the Alien (ALN, red), where the drill bits are placed directly at the core barrel front. 1A and 1E are not displayed as coring was restricted to surface sediments (< 5 m) using the HPC. The core composite (cc) is based on core correlation of individual holes based on field depth measurements. White parts indicate no core recovery due to gaps. The lithology (lith.), total organic carbon (TOC), total inorganic carbon (TIC), and stable isotope ($\delta^{18}O_{calc.}$, red dots in the TIC curve, and $\delta^{13}C_{calc.}$ to the right) measurements are based on core catcher samples. Magnetic susceptibility (MS) was measured in 2 cm intervals on a multi-sensor core logger (MSCL) equipped with a whole core loop sensor. Spectral gamma ray (GR) is based on downhole logging data run through the drill pipe with 10 cm vertical resolution. The grey bar indicates tentatively the Middle Pleistocene transition (MPT). Marine isotope stages (MIS) 11 and 31 are extrapolated from glacial/interglacial changes in TIC contents.

during pre-site surveys between 2005 and 2009 have already shown that TIC is a valuable proxy for short-term and long-term climate change over the last ca. 135 ka (Vogel et al., 2010a; Wagner et al., 2010). TIC is high during interglacials and primarily originates from calcite precipitation. During glacial phases carbonate is almost absent. In the core catcher samples from the DEEP site, very low TIC characterizes the coarser sediments below 430 m b.l.f. (Fig. 5). This indicates that fluvial conditions prevailed at the onset of the existence of Lake Ohrid and that the clastic detrital matter supplied does not originate from the calcareous Galiçica mountain range to the east of the lake (Fig. 1), where the main inlets are located today. At 430 m b.l.f. TIC significantly increases upcore to slightly more than 10 %. This implies that the lake had established and relatively warm conditions in combination with higher productivity that caused intense calcite precipitation. Between 430 and 315 m b.l.f. TIC, data show distinct high-frequency fluctuations. This can probably be attributed to the dominant 41 ka obliquity cycle prior to 920 ka (Mudelsee and Schulz, 1997; Tzedakis et al., 2006), and the

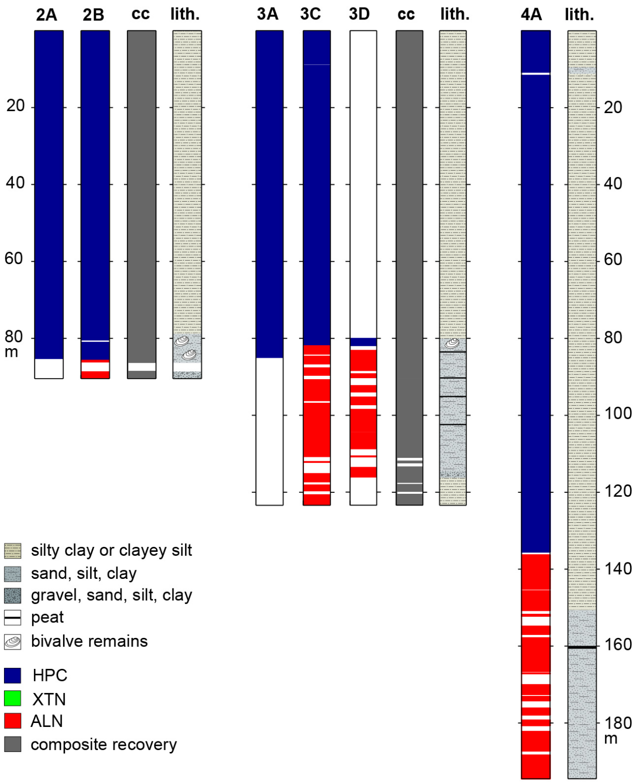

**Figure 6.** Core recovery and lithology from Cerava (2A and 2B), Gradište (3A, 3C, and 3D), and Peštani (4A) sites. Colours indicate different coring tools used (cf. Fig. 5). White sections in the core composites (cc) of each site indicate no core recovery.

highest TIC peak at ca. 360 m b.l.f. is tentatively correlated with the Marine Isotope Stage (MIS) 31 (Fig. 5). The sequence between 315 and 250 m b.l.f. exhibits a decrease in TIC frequency, which probably corresponds to the Middle Pleistocene transition (MPT) between 920 and 640 ka. The uppermost 250 m indicate similar amplitudes in TIC fluctuations, ranging between almost 0 % and 10 %, but fluctuating at a lower frequency. This variability can be attributed to 100 ka cycles, which have dominated since 640 ka. As interglacial periods should correspond with high TIC, the MIS 11 and MIS 5 sediments in the DEEP site record would occur at ca. 175 and 50 m b.l.f., respectively (Fig. 5). This is supported by the occurrence of several tephras, which are identical to those identified previously during analysis of cores from pre-site surveys (Sulpizio et al., 2010; Vogel et al., 2010b). For example, a coarser horizon at 18 m b.l.f., which is characterized by a maximum in MS and gamma ray data (Fig. 5), corresponds with the Y-5 tephra (Campanian Ignimbrite). This is the most prominent tephra in all other records from Lake Ohrid and was deposited 39.3 ka (e.g. Sulpizio et al., 2010). Numerous peaks in the MS data suggest that the DEEP site will become an outstanding distal record of the activity of Italian eruptive volcanoes and perhaps the “Rosetta Stone” for regional tephrostratigraphy. The low organic matter content in all core catcher samples from the DEEP site sequence, such as reflected by TOC values of $< 3\,\%$ (Fig. 5), suggests that the lake has had an oligotrophic state throughout its entire existence.

## 4.3 Diatom data

Preliminary diatom data were generated from core catcher samples at ca. 3 m resolution from two boreholes (1B and 1C) at the DEEP site. Results for 1C are presented here (Fig. 7). A total of 173 smear slides was prepared, and ca. 100 diatom valves per slide were counted under oil immersion at × 1500 magnification with a Nikon Eclipse 80i light microscope (LM) equipped with a Nikon Coolpix P6000 digital camera. Counts were converted into percentages and displayed using Tilia and TGView v. 2.0.2. (Grimm, 2004). Diatom identification was aided by reference to the taxonomic keys of Krammer and Lange-Bertalot (1986–1991) and dedicated Ohrid and Prespa taxonomic works (Hustedt, 1945; Jurilj, 1954; Levkov et al., 2007, 2012; Cvetkoska et al., 2012). Diatoms were preserved throughout the uppermost 480 m of the sediment sequence, comprising 122 diatom taxa. Although the benthic group is the most species-rich (60 % of taxa), the sequence above 430 m b.l.f. is dominated by planktonic species ($> 85\,\%$). At the base of the sequence, the initially poor preservation in a coarse substrate (480–430 m b.l.f.) strengthens the interpretation of a shallow water body; the gradual increase in relative abundance of planktonic taxa from 430 to 320 m b.l.f. probably reflects the initial infilling of the lake basin, with a stable and deep water body thereafter. Major shifts at 430 m, 320 m, 230 m and 80 m b.l.f. are likely to represent key stages of evolution and/or environmental change, the first of which corresponds to the key boundary identified between shallow and deeper lake states. There is clear evidence for evolution within the dominant planktonic genus, *Cyclotella*. The replacement of *C. iris* by *C. fottii/hustedtii*, the similar morphological characteristics of which indicate that they are likely to have similar ecological niches, probably represents an excellent example of rapid species turnover. Apparently close correlation with geochemical proxies, and carbonate in particular, suggests that major shifts in diatom-species assemblage composition are driven by glacial/interglacial climate cycles in the latter part of the record. Our previous diatom-based palaeoclimate analysis of sequences spanning the last 134 ka, from the last interglacial to present (Wagner et al., 2009; Reed et al., 2010; Cvetkoska et al., 2012), demonstrates the high sensitivity of diatoms to glacial/interglacial and interstadial climate change, driven primarily by temperature-induced productivity shifts. This is supported by modern ecological data, which define the epilimnetic vs. hypolimnetic life habit of dominant planktonic taxa (Allen and Ocevski, 1976). The same suite of dominant taxa prevails in the DEEP sequence above 230 m b.l.f., giving good modern analogues for future

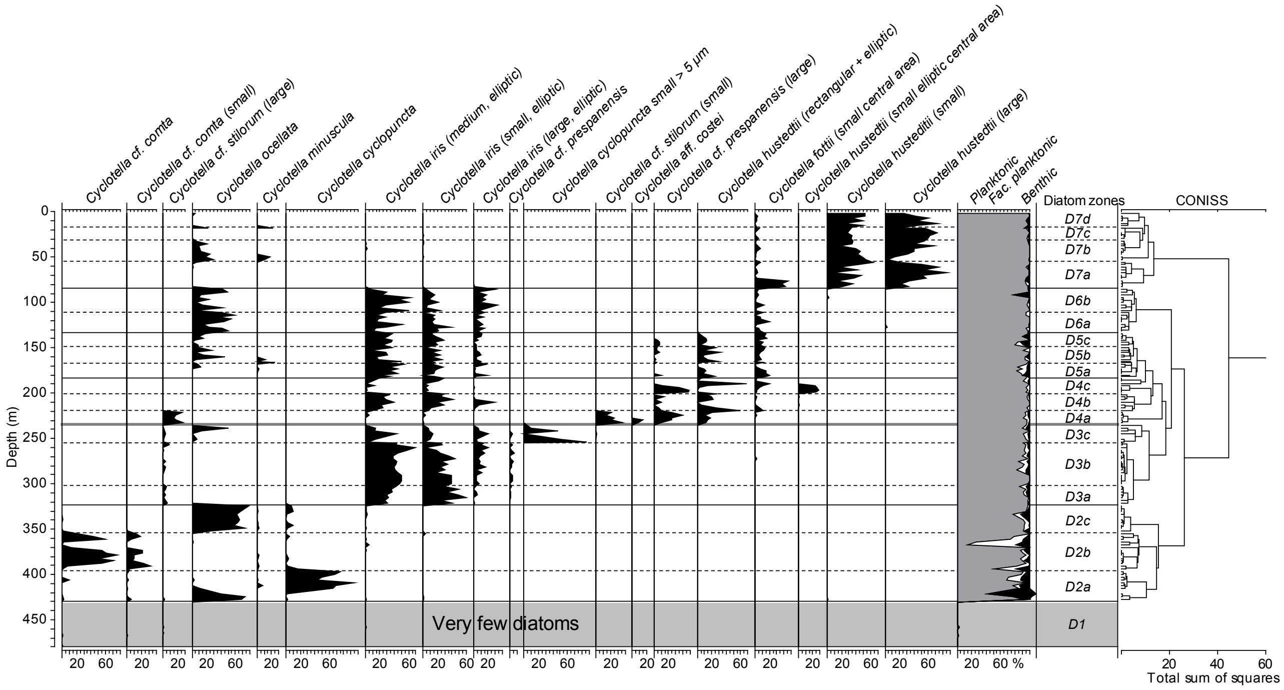

**Figure 7.** Preliminary diatom data from smear slides of core catcher samples (hole 1C, DEEP site).

palaeoenvironmental reconstruction. Analogues are poor below this depth, underlining the degree to which Quaternary diatom evolution has probably occurred, but the presence of dominant taxa such as *Cyclotella iris* in oligotrophic fossil assemblages (Krammer and Lange-Bertalot, 1991a) provides a strong baseline from which to reconstruct earlier Quaternary palaeoclimates in the lower record.

## 4.4 Stable isotope data

Stable isotope analysis of carbonate was conducted using sediment aliquots from 69 samples with $> 1\,\%$ TIC (hole 1B, core catchers). Subsamples were processed to remove organics and measured for stable isotope ratios. The data show $\delta^{18}O_{\mathrm{calcite}}$ values increasing through the core, ranging between $-7.6$ ‰ and $-2.9$ ‰, and averaging $-5.2$ ‰ $\pm 1.1$ ‰ (Fig. 5), which is most likely the result of greater freshwater input and lower lake-water residence times in earlier interglacials. From modern calibration data sets, $\delta^{18}O_{\mathrm{calcite}}$ in Lake Ohrid is known to be a function of inflow and evaporation (Leng et al., 2010), so significant positive excursions suggest periods of exceptional aridity and potentially lower lake levels (for example at 50, 210 and 310 m b.l.f.), which coincide with high TIC phases (interglacial periods). $\delta^{13}C_{\mathrm{calcite}}$ ranges ($-2.1$ ‰ to $+2.1$ ‰, mean $=0.0$ ‰ $\pm$ 0.8 ‰) are consistent with the catchment geology providing a major source of inorganic carbon ($\delta^{13}C_{\mathrm{catchment}} = +1$ ‰) enhanced by longer residence times allowing increased exchange with atmospheric $CO_2$ towards the top of the sequence.

**Figure 8.** Rounded gravel and pebbles in core catcher material (DEEP site, hole 1D at 569 m b.l.f.) indicate fluvial transportation.

Overall, the patterns seen in borehole logging, MS and core-catcher data imply that the record from the DEEP site covers the entire history of extant Lake Ohrid. Rounded pebbles and gravel from the base of the sediment record (Fig. 8) imply that fluvial sedimentation prevailed in the Lake Ohrid basin before the basin was filled, culminating in the development of the deep modern lake. A stepwise decrease in grain size from the base to 430 m b.l.f. is attributed to the establishment of lacustrine conditions and increasing lake levels. According to TIC, MS, and borehole gamma ray values, the uppermost 430 m b.l.f. cover probably > 1.2 Ma. Major hiatuses or mass-wasting deposits were not observed at this site.

## 5 Ongoing and future work

The sediment cores recovered during the SCOPSCO 2013 field campaign at Lake Ohrid are stored at the University of Cologne, Germany, where core opening, description, documentation, and initial analyses such as MSCL and X-ray fluorescence (XRF) scanning are taking place. The primary focus of current studies is the sediment sequence from the DEEP site. For the XRF scanning, intervals are set to 2.5 mm, which likely provides a decadal resolution. Visual inspection, MS and XRF scanning data will be used to identify horizons with tephras or cryptotephras. Such horizons will be sampled and tephra identification will be carried out (cf. Vogel et al., 2010b; Damaschke et al., 2013). The results combined with palaeomagnetic measurements and chronostratigraphic tuning will be applied to establish an age model.

Subsampling for geochemical, pollen and diatom analyses will be carried out at consistent intervals of 16 cm on the composite core after core correlation based on visual inspection and XRF data. Based on an estimated average sedimentation rate of ca. 30 yrs cm$^{-1}$ (430 m sediment column corresponding to ca. 1.2 Ma), the 16 cm intervals correspond to a resolution of ca. 500 years. Shorter intervals with higher temporal resolution are envisaged for future studies to investigate, for example, glacial to interglacial transitions or other selected events.

Core opening, description and documentation, and analyses of the Cerava, Gradište and Peštani sediment sequences will be carried out after the DEEP site. Combining the DEEP site with the peripheral drill sites will allow us to achieve the main goals of the SCOPSCO project. Altogether, this makes Lake Ohrid a key site of global importance for improving our understanding of Quaternary environmental change in the northern Mediterranean and general triggers of evolutionary events.

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Scientific Drilling
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# The shallow boreholes at The AltotiBerina near fault Observatory (TABOO; northern Apennines of Italy)

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**Abstract.** As part of an interdisciplinary research project, funded by the European Research Council and addressing the mechanics of weak faults, we drilled three 200–250 m-deep boreholes and installed an array of seismometers. The array augments TABOO (The AltotiBerina near fault ObservatOry), a scientific infrastructure managed by the Italian National Institute of Geophysics and Volcanology. The observatory, which consists of a geophysical network equipped with multi-sensor stations, is located in the northern Apennines (Italy) and monitors a large and active low-angle normal fault.

The drilling operations started at the end of 2011 and were completed by July 2012. We instrumented the boreholes with three-component short-period (2 Hz) passive instruments at different depths. The seismometers are now fully operational and collecting waveforms characterised by a very high signal to noise ratio that is ideal for studying microearthquakes. The resulting increase in the detection capability of the seismic network will allow for a broader range of transients to be identified.

## 1 Introduction: scientific background

Scientists' ability to integrate geological, seismological and laboratory observations related to earthquakes and faulting are essential for opening new paths of discovery and increasing our understanding of fault mechanics. The main difficulty in reconciling multidisciplinary observations is the scale dependence, which characterises the underlying physical processes that are inherent to each discipline. To tackle this challenge, the main prerequisites are the availability of high-resolution data and access to state-of-the-art research infrastructure that allow for the analysis of innovative and original data sets.

To lower the minimum earthquake detection threshold and to enhance the resolution of the signals recorded by our seismic network, we decided to build a seismological antenna at depth. These field observations complement the laboratory data produced by a newly built biaxial rock deformation apparatus within a pressure vessel (Collettini et al., 2014) capable to record acoustic transients emitted from deforming rock samples.

The instrumented boreholes are part of The AltotiBerina near fault ObservatOry (TABOO; http://taboo.rm.ingv.it/; Chiaraluce et al., 2014), a scientific infrastructure managed by INGV (Istituto Nazionale di Geofisica e Vulcanologia). The infrastructure consists of sites equipped with multisensor stations (seismometers, GPS, geochemical and electromagnetic sensors), devoted to the monitoring of a 60 km-long active normal fault system located along the northern Apennines of Italy (Fig. 1).

The fault system monitored via TABOO is dominated by the Alto Tiberina fault (ATF), a low-angle normal fault dipping in the range of 15–20°. In the same area, moderate to large earthquakes seem to nucleate on steeply dipping normal faults antithetic to ATF (Fig. 1). The ATF is oriented at high angle to the maximum vertical compressive stress, $\sigma_1$, and is therefore severely misoriented within the active stress field (Collettini and Barchi, 2002). The ATF, as many other low-angle normal faults (LANF) around the world (Collettini et al., 2011), formed as a gently dipping structure and is characterised by a high and constant rate of microseismic activity (Chiaraluce et al., 2007). These observations, collected in the

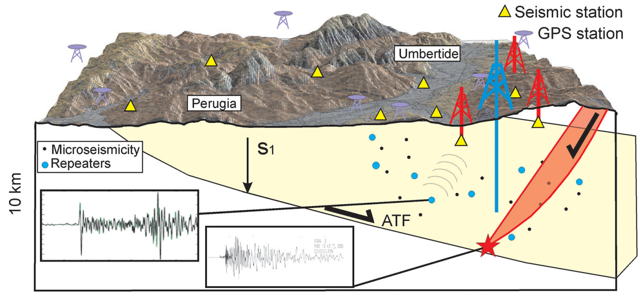

**Figure 1.** Illustration showing the geological and geophysical characteristics of the TABOO test site.

last ten years, pose numerous questions such as the following: how can a LANF initiate at a high angle to the maximum compressive stress? What are the physical properties of the fault rocks? Does the fault generate only microseismicity, by the reactivation of localised fault patches, or also large earthquakes with a magnitude of up to 7 that can break the entire fault surface? To answer these questions, we have developed an interdisciplinary research project addressing the mechanics of seismic vs. aseismic deformation.

Here we report on site selection and instrumentation, and discuss the quality of background data.

## 2 Site selection

We selected our chosen sites for the seismological antenna (Fig. 2; a zoom of the area inside the box is found at the bottom left) for two reasons. First, the location of a nearby deep borehole (Mt. Civitello; 5.6 km depth) that is one of the deepest wells drilled by the Italian National organisation for Hydrocarbons (ENI). Borehole and laboratory *P* wave velocities (Trippetta et al., 2010, 2013) have been integrated with *P* wave velocities obtained from best migration analysis of the seismic reflection profiles (Mirabella et al., 2011) and earthquake data collected by TABOO (Latorre et al., 2014) to develop a detailed one-dimensional velocity model for earthquake locations (Table 1).

Furthermore, observations of microseismic activity (including repeating earthquakes), which might be related to the ATF, nucleate at 5 km depth. Second, the ATF is a potential target for a deep-drilling project (Multidisciplinary Observatory and Laboratory of Experiments along a drilling in central Italy; MOLE). An ICDP (International Continental scientific Drilling Program)-funded workshop was held in May 2008 (Cocco et al., 2009) to analyse its scientific and technological feasibility. One major outcome of the workshop was a determination that to sample uncompromised fault rock from seismogenic depth would require a borehole with a total depth of 5–6 km. This borehole would target the source regions of repeating microearthquakes and sample those fault rocks. An array of seismometers at depth, producing low noise signals, will monitor microseismic events that occur at a depth shallower than 5 km.

The geometry of our boreholes forms a triangle centred on the deep borehole (Mt. Civitello in the bottom left zoom of Fig. 2) with a mean distance between the sites of about 3 km.

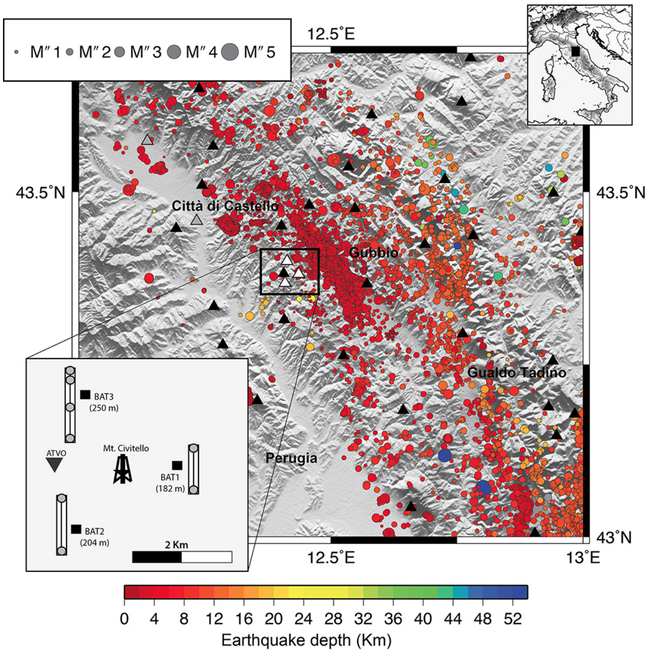

**Figure 2.** Map of the study area. Circles show the ≈ 12 000 earthquakes that occurred from July 2012 through December 2013. They have been both scaled in size according to the local magnitude ($M_L$) of the events and colour-coded based on their hypocentral depth. The black triangles represent surface stations while the white and grey triangles show borehole stations. At the bottom left, we show a zoom of the area where the three boreholes (BAT1, BAT2 and BAT3) are located. The black icon in the centre is the location of the Mt. Civitello deep borehole while the upside-down triangle is a permanent station (ATVO).

### Drilling operations and borehole instrumentation

All boreholes are hosted in the same lithology: the Miocene Marnoso Arenacea (marly-arenaceous turbidites in Table 1) formation. Around the seismological antenna, this formation consisting of marls and arenaceous rocks is characterised by an average thickness of about 1 km. Under ambient pressure, the density of the lithology measured in the laboratory is about 2.46 g cm$^{-3}$ and the connected porosity ranges from 2.2 to 13.8 % (Trippetta, personal communication, 2014).

The holes were drilled with a traditional rotary drilling technique and did not include any coring operations. We used drill rods of diverse diameters and weights. Drill collars were connected to the drill bit to keep the drill string straight. We used a drill bit designed for medium-hard rock types that had

**Table 1.** Average *P* wave velocity for the lithologies encountered in the Mt. Civitello borehole.

| *P* wave velocity (km $s^{-1}$) | Borehole | Laboratory | Seismic profiles | Seismology |
|---|---|---|---|---|
| Marly-arenaceous turbidites | 4.0 | 4.0 | 4.0 | 4.0 |
| Carbonates | 5.6 | 6.0 | 5.5 | 5.5 |
| Triassic evaporites | 6.3 | 6.4 | 6.1 | 6.1 |

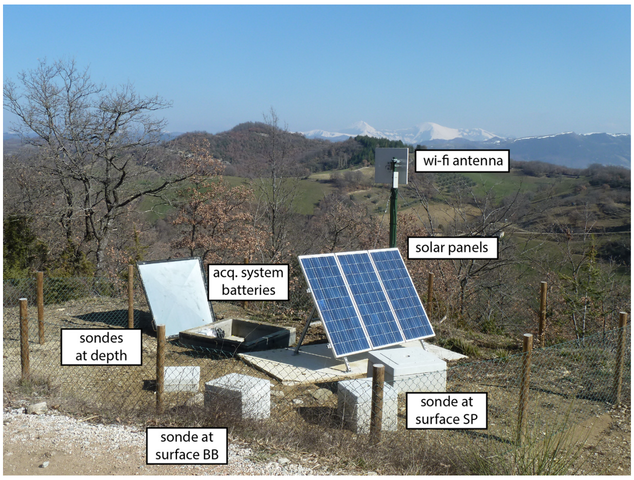

**Figure 3.** An example of a site hosting the seismic instruments: BAT2 station. The solar panels provide power to the acquisition and transmission system (Wi-Fi antenna). In the case of a lack of sun, there is a set of batteries that can power the station for about ten days. There are three concrete boxes accommodating the broadband (BB) and short-period sensors located at the surface plus the well-head with the cable connecting the seismometer at depth with the acquisition system.

a diameter of 165.1 mm (6 1/2 in.). The rate of penetration was generally quite regular, ranging from 2.65 to 3.75 m $h^{-1}$.

To ensure a better insulation of the sensor from surface noise and a better coupling of the seismometer with the surrounding rocks, we decided to case only the first 9 m of the boreholes with a temporary iron casing (220 mm).

Due to the local lithology conditions and the stability of the boreholes, we were able to avoid casing in two sites (BAT1 and BAT2). After the completion of drilling, the instruments were lowered and cemented in, with cement filling the borehole to about 10 m above the sensors. The cement was mixed with rock salt in order to increase the settling time. The remaining portions of the boreholes were filled with sand, to avoid cable torsion in the case of large seismic events.

At the third site (BAT3), we encountered problems while drilling. At about 180 m depth, we experienced near total loss of the drilling fluid into the formation. We suspect that this probably occurred due to the intersection of the borehole with a highly fractured zone. For this reason, we installed a plastic casing (polyvinyl chloride, PVC) within the entire borehole to avoid loss of the borehole.

The three boreholes were drilled to different total depths: 182 m (BAT1), 204 m (BAT2) and 250 m (BAT3). This difference was by design as we halted drilling once we encountered less fractured, more competent lithologies, at a depth of around 200 m in BAT1 and BAT2. Each borehole is equipped with a sensor at the bottom of the hole and at the surface, while the deepest borehole (BAT3) has a vertical array, with a sensor every 100 m (50, 150 and 250 m).

The sensors consist of three-component short-period (SP) seismometers with a natural frequency of 2 Hz. The signal is sampled at 500 Hz. The instruments are passive geophones installed inside 1.06 m long steel housing with a diameter of 8.8 cm and a weight of 30 kg. We decided to install SP passive instruments as we mainly deal with small to moderate earthquakes that have a more interesting bandwidth toward the higher frequencies. A sampling rate of 500 Hz allows for a complete recording up to 200 Hz. Moreover, by using passive sensors, we do not need a power supply in the boreholes, which can be a source of complications for long-term experiments.

The three sites have also been equipped with additional short-period and broadband seismometers positioned at the surface (SP and BB respectively in Fig. 3, where we show a picture of BAT1 site) to allow for a better comparison and association between data collected by both seismometers at depth and the other stations of the TABOO network.

The TABOO network has two additional short-period seismometers installed inside shallow boreholes further to the north (grey triangles in Fig. 2). They were installed by INGV in early 2000. As these sensors are installed within the unconsolidated alluvial sediments of the Tiber valley and are mainly used for the analysis of site effects, they do not produce high-quality data. Our decision to drill in the Marnoso Arenacea formation was based on this experience.

Power at the remote sites is supplied by solar panels. The dedicated transmission system is composed of a Wi-Fi antenna linked to a radio backbone (Fig. 3) and transmits data in real time to the INGV acquisition centre located about 80 km away.

The three sites are now completely operative and record high-quality data characterised by a high signal to noise ratio (S / N). They enhance the detection capability of the local area down to negative magnitude events (Chiaraluce et al., 2014). In Fig. 4a and b, two power spectral densities from

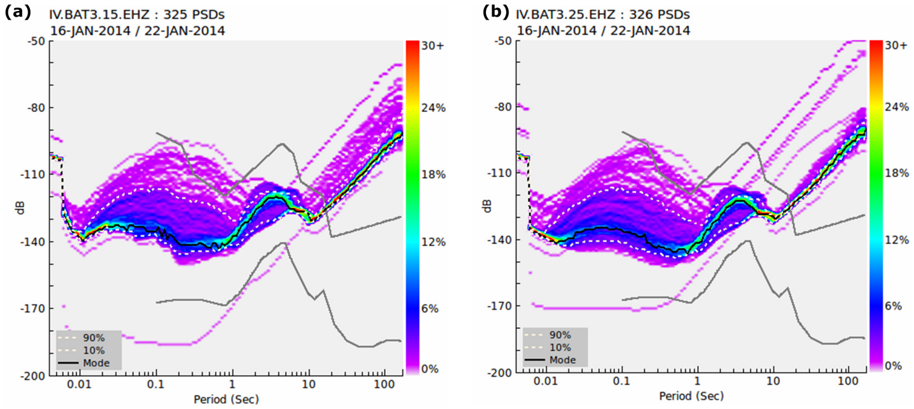

**Figure 4.** Power spectral density computed from data recorded during one week at BAT3 at a depth of 150 **(a)** and 250 **(b)** m.

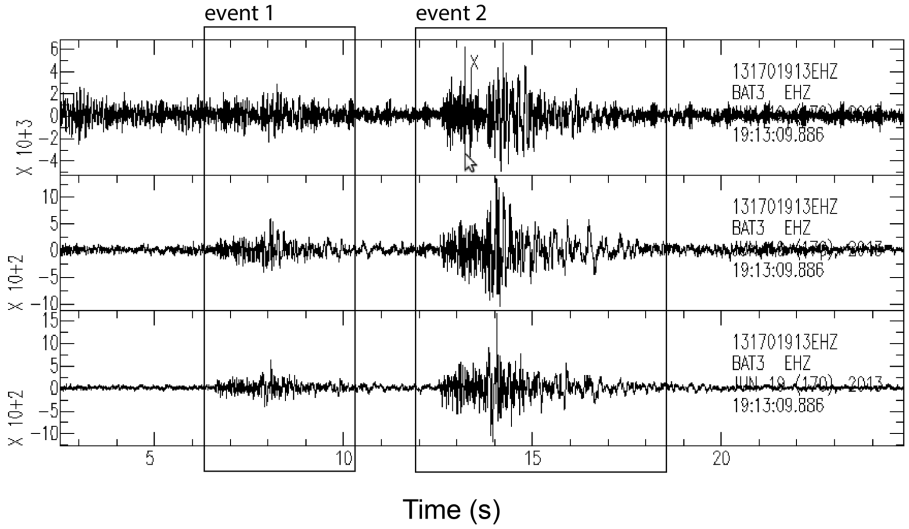

**Figure 5.** Two small earthquakes recorded at BAT3. Top trace: surface sensor. Middle trace: sensor at 150 m. Bottom trace: bottom sensor (250 m).

one week of recording at station BAT3 by the sensors installed at a depth of 150 and 250 m are shown. It is evident that at high frequencies, the noise level is significantly reduced in the deeper sensor. Also, the high number of earthquakes (bell-shaped spectra in the period band 0.01–10 s) recorded by both sensors is significant.

Figure 5 compares the recording of two low-magnitude earthquakes (local magnitude −1.0 and −0.6) for station BAT3 by sensors at the surface, 150 m depth and 250 m depth. It is evident that the deepest sensor is suitable to record even smaller earthquakes, while at the surface only the larger event is recognisable and characterised by a more complex waveform.

## 3 Results and conclusions

Figure 2 shows a map view of the seismicity we gathered with the TABOO seismic network which includes seismic stations at the surface (black triangles) and is complemented by the stations at depth (white and grey triangles). We indicate the position of BAT1, BAT2 and BAT3 (white triangles inside the black box highlighting the zoomed-in area in Fig. 2) relative to both the entire network and the seismic activity. About 12 000 earthquakes, $-1.2 < M_\mathrm{L} < 3.9$, were recorded from July 2012, when all the three borehole stations were connected to the acquisition system, through to December 2013. The contribution of the borehole stations to the network is highly significant. In the cited time span, 33 520 *P* wave arrival times were obtained from the borehole recordings of the deepest sensor in each well. The capability to record more than 90 % of the events that occurred in the area also testifies to the robustness of the equipment and study site.

The earthquakes have been colour-coded based on their hypocentral depth to point out the location of seismicity and the array relative to the ATF geometry. The boreholes are positioned above the shallow seismicity that nucleates on the ATF at about 5 km depth. Our expectation is to detect nearly 100 % of the microearthquakes occurring on the ATF plane at shallow depths. As a consequence, the costs of a potential deep-drilling experiment, would greatly decrease.

We are planning additional instrumentation of TABOO including the construction of a strain-metre array. The aim is to enlarge the spectrum of the observed deformation mechanisms. In this way we can additionally reduce the gap between natural and experimental earthquakes and try to improve our understanding of the physics behind the process.

Our end goal is to compare natural and lab observations. With the borehole seismometers we are almost able to record the full range of (high) frequencies characterising the source of small earthquakes occurring in situ on sub-metre-scale faults (e.g. local magnitude −1.0 in Fig. 5). While in the laboratory, we will reproduce microearthquakes on relatively large $20 \times 20\ \mathrm{cm}^2$, fluid-rich experimental faults sheared at in situ boundary conditions.

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# A new hybrid pressure-coring system for the drilling vessel *Chikyu*

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**Abstract.** Retrieving core samples without releasing the in situ hydrostatic pressure during core recovery is one of the many technical challenges in scientific drilling. We report here a newly developed hybrid pressure-coring system for the use on the drilling vessel *Chikyu* and its successful use during expeditions 906 and 802 in the Nankai Trough of Japan. The system is gas-tight and hence enables researchers to study in situ geophysical and geochemical characteristics of sediments containing gaseous components, such as methane hydrates that cannot be reliably recovered with nonpressure coring systems. In addition, pressure coring is a powerful tool, not only for scientific but also for hydrocarbon resources research.

## 1 Introduction

The general concept of pressure coring as a technique has long been tested for scientific ocean drilling since the Deep-Sea Drilling Project (DSDP) in the 1980s. A pressure-coring barrel was first developed and tested for capturing methane hydrate-bearing sediments in the Blake Ridge (Kvenvolden et al., 1983). During the Ocean Drilling Program (ODP), the pressure core sampler (PCS; Pettigrew, 1992; Graber et al., 2002) was developed for the drilling vessel (D/V) *JOIDES Resolution*. Using the PCS, gas-rich or methane hydrate-bearing sediments were successfully retrieved from the western Pacific coast during ODP legs 164 (Dickens et al., 1997, 2000; Paull et al., 2000), 201 (Dickens et al., 2003) and 204 (Shipboard Scientific Party, 2003). During ODP leg 204 at the Cascadia margin, Fugro pressure corer (FPC) and the hydrate autoclave coring equipment (HYACE) rotary corer were also deployed on the D/V *JOIDES Resolution*, resulting in the successful sample recovery (Shipboard Scientific Party, 2003). During the Integrated Ocean Drilling Program (IODP), the same systems were used during expedition 311 on the *JOIDES Resolution*, and methane hydrate-bearing sediments were successfully recovered from 16 horizons of Hydrate Ridge on the Cascadia margin (Expedition 311 Scientists, 2005).

Besides scientific operations, pressure coring has been used for the exploration of natural hydrocarbon resources, including oil, gas and methane hydrates. For example, pressure-coring systems have been used for governmental resource survey of methane hydrates offshore of India, China and Korea using the *JOIDES Resolution* and other drilling vessels (Schultheiss et al., 2009). The Japan Oil, Gas and Metals National Corporation (JOGMEC) developed a pressure–temperature coring system (PTCS), and performed coring surveys for methane hydrates in the Nankai Trough of Japan (Fujii et al., 2010). The pressure-coring tools that have been developed so far are summarized in Table 1.

**Table 1.** Summary of available pressure-coring technique.

| | Drill pipe diameter (in) | Core OD (in) | Core length (m) | Max. pressure (Mpa) |
|---|---|---|---|---|
| ODP PCS | 5 or 5 1/2 | 1.575 | 1 | 69 |
| Fugro HYACE RC | | 2 | 1 | 21 |
| Fugro FPC | | 2.125 | 1 | 25 |
| JOGMEC PTCS | 6 5/8 | 2.625 | 3.5 | 24 |
| CDEX hybrid PCS | 5 or 5 1/2 | 2 | 3.5 | 35 |

However, prior to the current development there was no pressure-coring tool deployable through the bottom hole assembly (BHA) of the D/V *Chikyu*. Here we report development of a new pressure-coring system for D/V *Chikyu* and first offshore operations.

## 2 Design and use of hybrid pressure coring system

The newly developed hybrid pressure coring system (hybrid PCS) was designed mainly by a combined design of PCS and PTCS, with original modifications of the sealing function (Fig. 1). Similar to its predecessors, the hybrid PCS is a wireline-based hydraulically actuated pressure-coring system for 5 and 5 1/2 in. drill strings, and interchangeable to the hydraulic piston coring system (HPCS) and the extended shoe coring system (ESCS) on the *Chikyu*. The system can be latched in the BHA and rotates with the BHA during coring. Hence, the hybrid PCS cannot retrieve oriented cores. The maximum pressure is ~ 35 MPa (5000 psi) and the core sample of the hybrid PCS is 51 mm in diameter with a maximum core length of 3.5 m.

The hybrid PCS consists of three major subassemblies: (1) the upper assembly is composed of the running and retrieving tool; (2) the middle assembly for pressure control, which includes a pressurized nitrogen reservoir; and (3) the lower assembly for the sample autoclave (Fig. 1). Two types of cutting shoes are deployable with the hybrid PCS, depending on the lithological characteristics of the target formation: one extends 10 mm ahead of the bit and rotates with drill pipes, while the other has 50 mm extension without rotation.

In practice, the hybrid PCS is lowered by wireline through the drill string to land in the BHA. The hybrid PCS is rotated using the top drive via the latch and BHA drill string. During the coring process the drilling mud pumps maintain drilling mud flow down the drill string to keep the hole open as well as to cool and lubricate the coring drill bit. Once the core has been cut and the drilling mud pumps are stopped, the retrieving tool is lowered wireline and latched to the hybrid PCS. Pulling on the wire applies a force first to the inner latch of the hybrid PCS, which then releases the inner barrel. Lifting up the retrieving tool triggers the following actions: (1) the top seal of the autoclave is closed, (2) the lower ball valves of the autoclave are closed by spring force, (3) connection to the $N_2$ reservoir is opened and the pressure in the autoclave is kept at a predefined pressure that has been supplied from $N_2$ in accordance with regulator via drilling mud, and (4) the inner core barrel latch is released. These actions are completed in no more than a few seconds. The hybrid PCS can then be retrieved in the same way as with other wireline core barrels.

Once recovered on the deck, the closed inner barrel is removed from the hybrid PCS and transferred into a vertical pipe near the rotary table on the rig floor filled with

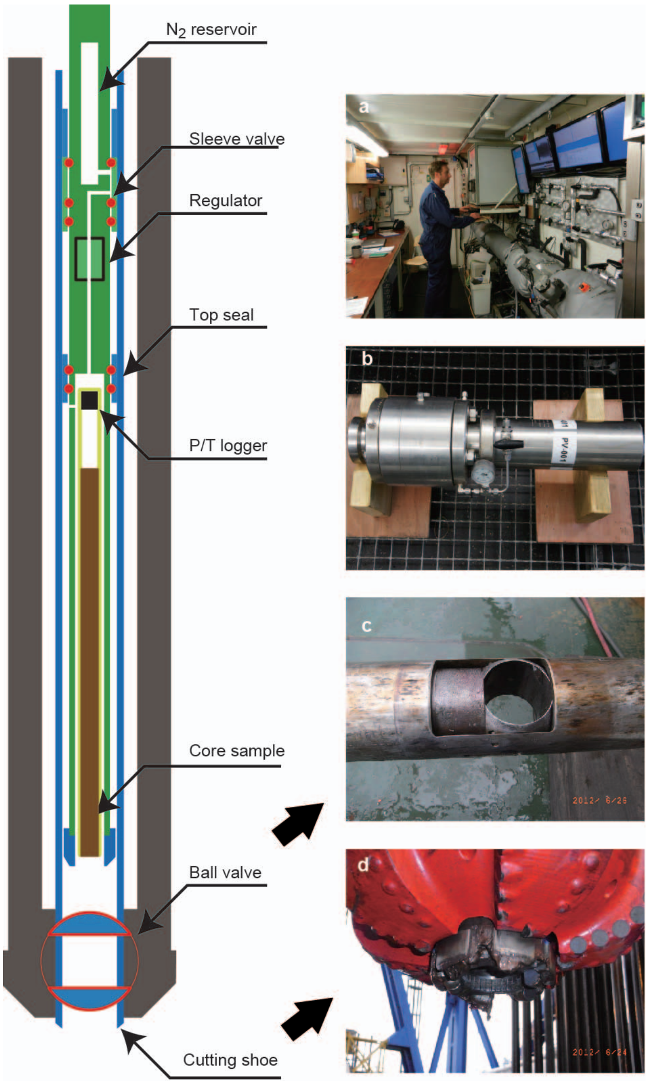

**Figure 1.** Schematic illustration of the hybrid pressure coring system showing the sealing mechanism by the top seal and the bottom ball valve. The autoclave is connected to the $N_2$ reservoir that supports the pressure at a predefined value. Pictures from expedition 906 show **(a)** a Geotek operator and equipment in the PCATS laboratory, **(b)** the storage chamber for a short sample (15 cm), **(c)** a closed ball valve in the hybrid PCS, and **(d)** the PDC drill bit with a short cutting shoe.

ice (mousehole). This cools the complete assembly to prevent dissolution/melting of any gas hydrate. After cooling for approximately 30 min, the sample chamber is connected to the Pressure Core Analysis and Transfer System (PCATS, Geotek Ltd.) for sample transfer and analysis. Pressure and temperature are recorded by the pressure–temperature logger in this autoclave system.

## 3 Onboard sample processing and analysis

The pressurized core is immediately transferred to the PCATS after cooling in the mousehole. The PCATS is housed in a three 20 ft container-based laboratory accepting up to 3.5 m long core. The core is transferred from the hybrid PCS to the PCATS pressure chamber using a linear manipulator and a rotator system (Schultheiss et al., 2009). During transfer of the pressurized core, nondestructive measurements of physical properties can be simultaneously acquired through the aluminum chamber, which includes X-ray CT imaging, gamma-ray and *P*-wave velocity measurements. Using all the data, especially the X-ray image, the core can be cut into subsections at selected positions. These subsections are stored in short pressurized sample chambers for postcruise analysis, or depressurized for further analysis and sampling in the onboard laboratory. Controlled depressurization provides an accurate volume measurement, and subsampling of gas from the sectioned sediment sample allows for accurate assessments of the volume and concentration of gas hydrate in the formation sampled.

## 4 Expedition 906

The hybrid PCS was first used on the *Chikyu* during expedition 906 from 26 to 28 June 2012 at the Kumano mud volcano no. 5 (hereafter KMV#5), which is one of the most active submarine mud volcanoes in the Nankai Trough (Kuramoto et al., 2001; Tsunogai et al., 2012). Site C9004 is located on the summit of KMV#5 (3367.581′ N, 13656.8085′ E; 1986.7 m in water depth), which was previously drilled with HPCS at hole C9004A down to 20 m below the seafloor (m b.s.f.) during the *Chikyu* expedition 903 in 2009. Based on onboard observations using an infrared thermo-view camera and X-ray CT scan, it was confirmed that HPCS cores at hole C9004A contained methane hydrates and breccia in the mud almost throughout the core, requiring retrieval of intact core samples to scientifically investigate hydrocarbons and other gaseous components such as hydrogen.

During expedition 906, we extended the drilling depth to ~ 200 m b.s.f. at hole C9004B by a combined use of HPCS, hybrid PCS and ESCS. A total of 11 cores were collected from hole C9004B, in which hybrid PCS was first tested at 4 selected depths (Table 2). Four coring operations of hybrid PCS at hole C9004B were trial-and-error processes to fix and/or adjust unexpected mechanical problems on the system.

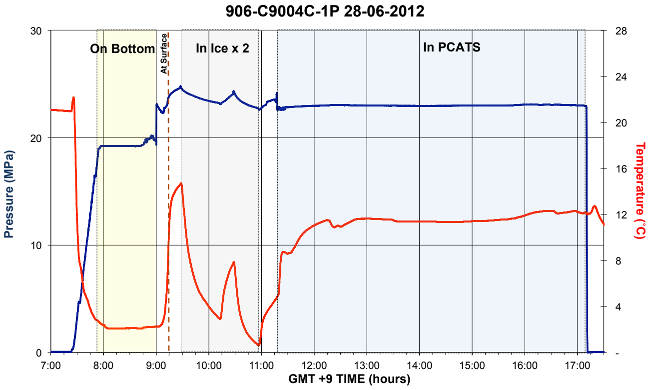

**Figure 2.** Pressure and temperature log from core C9004C-1 showing that the pressure in the autoclave was kept higher than the in situ pressure through retrieval, onboard handling and analysis.

The first trial of the hybrid PCS core (C9004B-3P) resulted in no recovery due to a sealing failure and an unpressurized chamber. The second core C9004B-5P was sealed at 18 MPa, which was slightly lower than the hydrostatic pressure at the coring depth. The rig floor handling of the core, including cooling in the mousehole, took approximately 2 h, during which the core was outside the methane hydrate stability field for 7 min. Observations with PCATS showed that the recovered core sample was small in volume and heavily disturbed; therefore, the core was depressurized onboard. The third core C9004B-7P was also small in volume and disturbed, and did not seal completely until very close to the rig floor. A small increase in pressure after sealing was observed, possibly due to dissolution of methane hydrates. The fourth core C9004B-9P was successfully sealed at 16 MPa, indicating the autoclave and ball valve system worked properly near the sea floor. However, it was found to be an empty core barrel. An HPCS core from the nearby depth intervals suggested that the poor core recovery was due to breccia in the soft, muddy matrix.

After reaching 203.5 m b.s.f. at hole C9004B, we drilled a new hole, C9004C, to test the hybrid PCS near the seafloor. The fifth core, C9004C-1P, was sampled by jetting in from the mudline to 6.5 m b.s.f. The pressure sensor deployed in the hybrid PCS indicated that the autoclave chamber successfully sealed at 3 MPa higher than the in situ pressure (23 MPa, Fig. 2). Observations using a X-ray CT scan from PCATS revealed an approximately 70 cm long sediment core containing veins filled with methane hydrate and mud clast in a soft mud matrix in the autoclave chamber (Fig. 3). The core was cut into eight sections. Four short sections were transferred into 15 cm long aluminum storage chambers and stored at 4 °C for shore-based analyses (Fig. 1b). The remaining three sections and one core catcher sample were used for

**Table 2.** Coring summary of expedition 906. H: hydraulic piston coring system, X: extended-shoe coring system, P/T: hybrid PCS with short extended shoe, P/X: hybrid PCS with long extended shoe.

| Core | Hole | Type | Top depth (m b.s.f.) | Bottom depth (m b.s.f.) | Advance (m) | Initial core length (m) | Initial recovery (%) | Pressure (MPa) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B | H | 0.0 | 4.0 | 4.0 | 9.68 | 242.0 | – | Highly expanded, unconsolidated silty clay with pebbles. Mudline was determined after X-ray CT scan. |
| 2 | B | H | 14.5 | 22.2 | 7.7 | 7.72 | 100.3 | – | Partial penetration. Highly expanded and core top was lost due to blow-off on the drill floor. Unconsolidated silty clay with pebbles. |
| 3 | B | P/T | 24.0 | 27.0 | 3.0 | 0.05 | 1.7 | 0.1 | Failed to keep in situ pressure due to leak. |
| 4 | B | H | 50.0 | 59.0 | 9.0 | 9.75 | 108.3 | – | Partial penetration. Highly expanded and blow-off from top and bottom. Unconsolidated silty clay with pebbles. |
| 5 | B | P/T | 59.5 | 63.5 | 4.0 | 0.20 | 5.0 | 18 | Succeeded in keeping almost in situ pressure. |
| 6 | B | H | 100.0 | 105.5 | 5.5 | 6.10 | 110.9 | – | Partial penetration. Highly expanded and blow-off from the bottom. Unconsolidated silty clay with pebbles. |
| 7 | B | P/X | 109.5 | 113.5 | 4.0 | 0.20 | 5.0 | 0.4 | Not sealed until near the sea level. |
| 8 | B | H | 113.5 | 122.1 | 8.6 | 9.14 | 106.3 | – | Partial penetration. Unconsolidated silty clay with pebbles. |
| 9 | B | P/X | 190.0 | 194.0 | 4.0 | 0.00 | 0.0 | 16 | Sealed, but no recovery. |
| 10 | B | X | 194.0 | 203.5 | 9.5 | 1.27 | 13.4 | – | Plugged at CC. Pebbly mudstone. |
| 1 | C | P/X | 0.0 | 6.5 | 6.5 | 0.90 | 13.8 | 23 | Successfully sealed. Recovered a short but intact cylindrical core. |

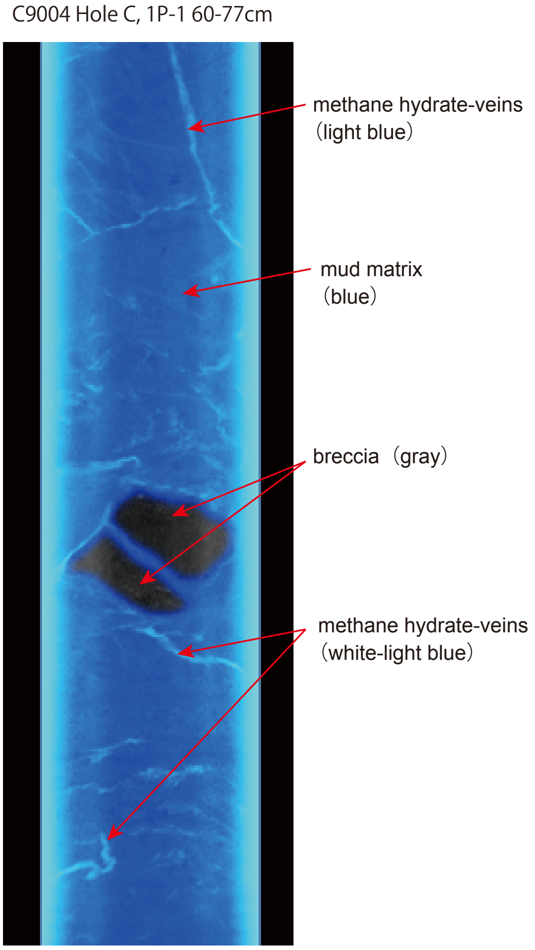

**Figure 3.** X-ray image of core C9004C-1P at full pressure in PCATS shows mud clast and methane hydrate veins in a matrix of hemipelagic mud.

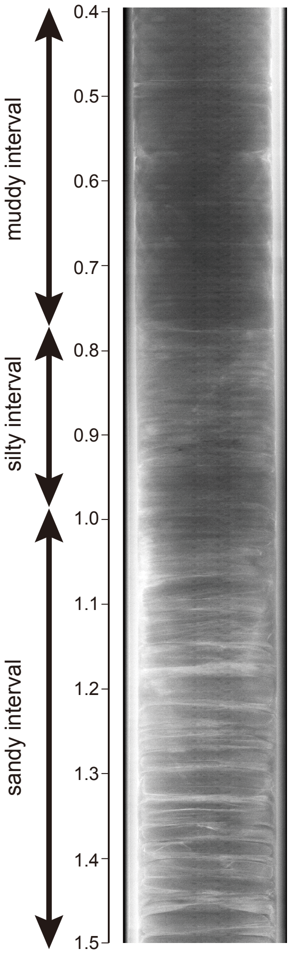

**Figure 4.** X-ray image of AT1-C-18P from expedition 802 shows clear image of lamina planes in turbidite structures. Sandy layers are highly saturated with methane hydrates. The image covers from 0.4 to 1.5 m of the core, and the diameter is 51 mm.

onboard subsampling and geochemical analyses (e.g., isotopic measurements).

## 5 Expedition 802

The hybrid PCS was subsequently used in the following *Chikyu* expedition 802, which was a commercial drilling campaign operated by JOGMEC and Japan Petroleum Exploration Company (JAPEX) in July 2012. The coring operation applying hybrid PCS was carried out as part of the reservoir characterization effort for a planned gas production test from methane hydrates on the north slope of Daini Atumi Knoll in the eastern Nankai Trough (Yamamoto et al., 2012).

The core hole (AT1-C) was drilled in the vicinity of a previously drilled monitoring borehole (AT1-MC) in which intensive geophysical operations have been done by LWD (logging while drilling) and wireline tools in February 2012, enabling measured core properties to be compared with logged in situ values. The coring interval was selected to cover around 45 m of methane hydrate-bearing sand–clay alternation layers and 15 m of overburden hemipelagic clay zone.

A total of 21 cores, including 18 pressure cores and 3 ESCS cores, were collected from the 60 m interval of the hole (262 to 322 m b.s.f.). The overall core recovery was 61 %, with 69 % achieved with the hybrid PCS cores. CT observation showed that the structure of the sediments was well preserved, and detailed lamina structures of turbidite sediment were clearly observed, as shown in Fig. 4. Of the 18 pressure cores taken, pressures > 12 MPa were maintained in 8 cores (Table 3). According to gas release of some of the pressure core, high saturation of methane hydrate (up to about 70 % fraction in pore space) was determined in some of the sandy intervals.

After the core recovery operation, the recovered cores were processed in three different schemes (Fig. 5). All of the Hybrid PCS cores were processed in PCATS with nondestructive analyses. The majority of well-pressure-preserved

**Table 3a.** Coring summary of expedition 802.

| | | |
|---|---|---|
| Net coring time | 17.5 h | |
| Number of cores | | |
| ESCS cores | 3 × 3 m | |
| Hybrid PCS cores | 16 × 3 m + 2 × 1.5 m | |
| Recovery rate | | |
| Entire interval | 36.82/60 m,<br>recovery rate 61 % | |
| Hybrid PCS | 34.99/51 m,<br>recovery rate 69 % | |
| Pressure condition | | |
| Pressure conserved cores (> 12 MPa) | 8 cores | 17.08 m |
| Partially pressure conserved cores (> 5.5 MPa) | 4 cores | 11.6 m |
| Pressure lost (< 5.5 MPa) | 6 cores | 6.31 m |

**Table 3b.** Place of analysis for pressurized and depressurized cores.

| Cores | Length | Place of analysis |
|---|---|---|
| ESCS cores | 1.83 m | *Chikyu* laboratory |
| Depressurized cores | 12.99 m | PCATS and *Chikyu* laboratory |
| Cores in pressure chamber | 22.00 m | PCCTs and AIST laboratory (shore-based) |

cores were stored in pressure vessels for future, more detailed analysis on shore. Some of the pressure cores were quickly cryo-frozen in liquid nitrogen to maintain gas hydrate stability. Such cores were used for measurement of petrophysical parameters in atmospheric pressure after surface conditioning. The remaining samples were treated following IODP protocols for geological description as well as geochemical/geotechnical and microbial analyses.

The samples were sent to onshore laboratories, including a facility of the National Agency for Advanced Industrial Science and Technology (AIST) in Sapporo equipped with a suite of core analysis devices for methane hydrate-bearing cores.

## 6 Perspectives

The hybrid PCS can be successfully deployed as a pressure-coring tool on the D/V *Chikyu*. It will be available for future scientific ocean drilling upon request from scientists, as well as for industrial operations that target hydrocarbon reservoirs such as natural gas accumulations and methane hydrates. With 3.5 m core length and 35 MPa maximum pressure, the hybrid PCS will provide excellent performance. The recovery rate will be increased in future through tests of different cutting shoes. It is also desirable to increase the efficiency of the onboard core transfer and subsampling under high pressure. These advancements will provide unprecedented opportunities to conduct geochemical, geophysical and biological analyses of gas hydrate-bearing sediment under in situ conditions. Use of the Hybrid PCS requires, on the other hand, careful planning for the operation and both onboard and onshore logistics. Potential users are therefore encouraged to contact CDEX at an early stage of proposal preparation.

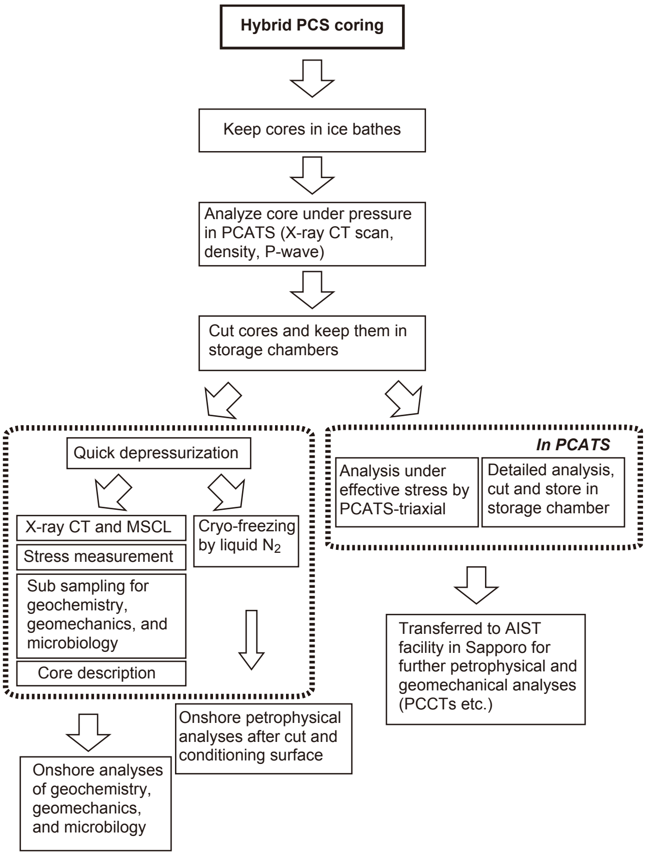

**Figure 5.** Schematic flow of the onboard core processing for Exp. 802. The obtained samples were processed in three different schemes. The majority of well-pressure-preserved cores were stored in pressure vessels for more detailed analysis on shore.

**Acknowledgements.** The construction of the hybrid PCS for the D/V *Chikyu* was supported by the Strategic Fund for Strengthening Leading-Edge Research and Development (JAMSTEC) and the Funding Program for Next Generation World-Leading Researchers (NEXT Program, F. Inagaki) by the Japan Society for the Promotion of Science (JSPS) and the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. The authors are grateful to the ship crew, drilling staff and laboratory technicians of expeditions 906 and 802 for their dedication and assistance with all aspects of the onboard operations. PCATS was operated by the team of Geotek Ltd., UK. The hybrid PCS was designed by Aumann and Associates, Salt Lake City, Utah. J. Aumann's contributions to the project were invaluable. Pressure Core Characterization Tools

(PCCTs) developed by the Georgia Institute of Technology (GIT) and the US Geological Survey were used for core analysis in AIST in January of 2013 under a collaboration project among AIST, GIT and JOGMEC. The authors would like to thank Peter Schultheiss and Kevin Grigar for their helpful and constructive comments on the manuscript.

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Scientific Drilling
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# Exploring new drilling prospects in the southwest Pacific

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**Abstract.** A major International Ocean Discovery Program (IODP) workshop covering scientific ocean drilling in the southwest Pacific Ocean was held in Sydney, Australia, in late 2012. The workshop covered all fields of geoscience, and drilling targets in the area from the Equator to Antarctica. High-quality contributions and a positive and cooperative atmosphere ensured its success. The four science themes of the new IODP science plan were addressed. An additional resource-oriented theme considered possible co-investment opportunities involving IODP vessels. As a result of the workshop, existing proposals were revised and new ones written for the April 2013 deadline. Many of the proposals are broad and multidisciplinary in nature, hence broadening the scientific knowledge that can be produced by using the IODP infrastructure. This report briefly outlines the workshop and the related drilling plans.

## 1 Introduction

The southwest Pacific is one of the most tectonically active regions on Earth, associated with large earthquake and volcanic events occurring on human time scales. The tectonics of this region are largely driven by deep earth processes that cause flows of material and energy among global reservoirs that affect major changes in Earth structure and composition. The area is also an important driver of global climate change and constitutes a key element of global thermohaline circulation. Future drilling of the sedimentary archives in the region will continue to yield vital information about the relative roles of ocean heat transport and greenhouse gas forcing on the warming and cooling of our planet, ice sheet stability and pole to equator climatic teleconnections. Drilling large igneous provinces will enhance our knowledge of the potential role of deep earth processes on the development of Earth's crust and atmosphere, and potential relationship with mass extinctions. Sampling plate boundary archives will increase our understanding of subduction initiation, earthquake and volcanic eruption frequency and volcanic arc formation. Installing borehole observatories at plate boundaries will allow

**Table 1.** List of proposals in the southwest Pacific region. Note: NR = riserless, R = riser and MSP = mission-specific platform drilling proposals.

| Proposal | Title | PI | Country | Platform |
|---|---|---|---|---|
| 567-Full4 | South Pacific Palaeogene | Thomas | USA | NR |
| 730-Pre2* | Sabine Bank Sea Level | Taylor | USA | MSP |
| 751-Full | West Antarctic Ice Sheet Climate | Bart | UK | NR |
| 781-MDP | Hikurangi Subduction Margin | Wallace | USA/NZ | R+NR |
| 781A-Full | Hikurangi Observatory | Saffer | USA | NR |
| 781B-Full | Hikurangi Riser | Wallace | USA/NZ | R |
| 799-Full* | Western Pacific Warm Pool | Rosenthal | USA | NR |
| 813-Pre | Antarctic Margin | Williams | USA | NR |
| 818-Pre | Brothers Arc Flux | de Ronde | NZ | NR |
| 831-APL | Campbell Drift Climate | Turner | USA | NR |
| 832-Full | Tasman Frontier Subduction | Sutherland | NZ | NR |

* Not discussed in this report.

megathrust slip processes and earthquake intensity to be investigated on human timescales. Drilling oceanic crust will reveal the nature of poorly known microbial communities and their potential role in processes related to the alteration of igneous crust, sedimentary diagenesis, hydrocarbon and mineral deposit formation and destruction. These processes will help reveal effects of microbes on subduction zone geochemistry, and potential influences of microbes on palaeoceanographic records. This region has also significant economic potential for mineral and petroleum resources. Collaboration among regional geological survey organisations and industry with the IODP through complementary drilling proposals will likely yield insights into deep and shallow earth processes.

## 2 Workshop goals

The southwest Pacific IODP workshop was hosted by Sydney University, Australia, in October 2012. An international group of eighty scientists reviewed the latest research about the region, discussed major questions that should be addressed with future deep ocean drilling through the International Ocean Discovery Program (IODP), and set up working groups to develop new drilling proposals in the region. The workshop covered all science themes of the new IODP science plan for 2013–2023 and an additional theme focusing on marine resource opportunities. A list of the current IODP proposals in the region is in Table 1.

### 2.1 Theme 1 – climate and ocean change: reading the past, informing the future

We recognise a major need for depth and latitudinal transects of sediment cores in the southwest (SW) Pacific, including the Pacific sector of the Antarctic margin, using a variety of ship-based and floating ice-based platforms, to address fundamental questions about past global change. This drilling will take advantage of the unusual opportunity that southwest Pacific topography offers for obtaining meridional core transects at relatively shallow water depths from the tropics to the polar region. This includes the Lord Howe Rise, which was identified as a special target for obtaining a north–south transect in the proposed SW Pacific drilling. The research expeditions proposed by April 2013 (Fig. 1) will investigate the relative roles of ocean heat transport and greenhouse gas forcing in the warming and cooling of Earth's climate, ice sheet stability and non-linear climate feedbacks, and pole to equator teleconnections. The work will also help to resolve current discrepancies existing between climate proxies and climate models.

#### 2.1.1 Palaeogene transect: tropics to Antarctica

The proposals in this subtheme share the common purpose of better understanding major shifts in temperature and other paleoenvironmental gradients between the tropics and the Southern Ocean during the greenhouse world of the early Palaeogene. The expeditions will test hypotheses posited to better understand the now well-known extreme warmth at high latitudes during the early Palaeogene; the origin and development of the Southern Ocean and its role in driving global climate change; and the nature of major late Palaeogene cooling and growth of the Antarctic Ice Sheets during the Eocene-Oligocene transition (32 Ma).

#### 2.1.2 567-Full4: Palaeogene South Pacific latitude transect

This expedition has been proposed to investigate the subpolar Pacific climate, oceanographic structure, and biogeochemical cycling of the remarkably warm Eocene through the transition to icehouse conditions in the Oligocene during the development of major continent-wide Antarctic ice sheets.

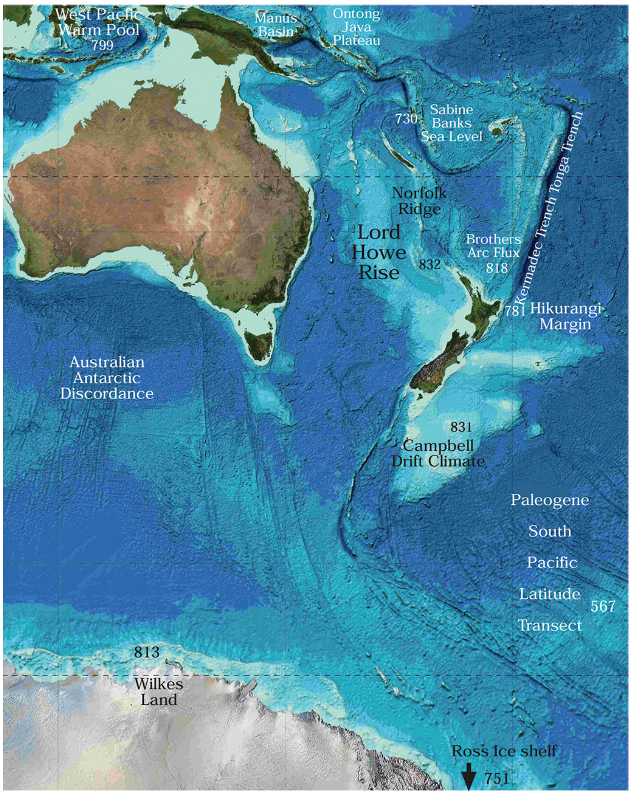

**Figure 1.** Location of existing drilling proposals in the southwest Pacific region. Base map adapted from General Bathymetric Chart of the Oceans (GEBCO) www.gebco.net. Proposals 730 and 799 are not discussed in this report.

### 2.1.3 813-Pre: Antarctic Cenozoic palaeoclimate (George V Land and Adélie Land shelves)

A proposal has been formulated for the use of seabed drilling in the recovery of two stratigraphic transects of shallow (~ 50 m) sites. The proximal sites are expected to yield more continuous Palaeogene and Neogene records than was possible during IODP 318 and provide further insight into Antarctica's climate evolution and its role in driving global climate change in the past.

### 2.1.4 831-APL: Campbell Drift climate (western Campbell Plateau and Campbell Drift)

Two regions on the Campbell Plateau are identified as having significant potential for paleoceanographic advances with possibilities of a single expedition or two linked expeditions to investigate the evolution of Cretaceous–Palaeogene climate and ocean circulation at high southern palaeolatitudes. Drilling would also use modern drilling technology at important sites drilled in earlier ocean drilling expeditions (e.g. DSDP (Deep Sea Drilling Program) site 277 and IODP site 1121).

### 2.1.5 Neogene and Quaternary climate and ocean change

The Neogene and Quaternary experienced the permanent development of the East Antarctic Ice Sheet during the mid-Miocene, and the full expansion of Southern Ocean sea ice by the mid-Pleistocene. Proposals will address major expansion of the West Antarctic ice sheet during the late Miocene, the history of West Antarctic Ice Sheet variability on the outer Ross Sea continental shelf and related oceanographic changes on the adjacent continental slope (751-Full), and the history of the East Antarctic Ice Sheet on the Wilkes Land continental shelf (813-Pre: summarised above).

## 2.2 Theme 2 – biosphere frontiers: deep life, biodiversity, and environmental forcing of ecosystems

The diverse geologic environments of the southwest Pacific and neighbouring oceanic regions provide numerous ideal opportunities to investigate many aspects of challenges related to a better understanding of the deep biosphere. Taking fullest advantage of these opportunities will require three different project strategies. A minimal strategy would be to have microbiologists, biogeochemists and other appropriate specialists participate in expeditions planned with other primary objectives. This strategy will typically involve shipboard and post-expedition microbiological and biogeochemical study of cores and logs collected for other purposes. Other projects will require the more dedicated strategy inherent in IODP ancillary project letters, which add relatively minimal additional drilling time to scheduled expeditions. Finally, some objectives would be best met with large-scale expeditions fully dedicated to drilling.

### 2.2.1 Subseafloor microbes and the world

Topics needing special attention include the influence of subseafloor microbes on Earth and ocean history, the influence of subseafloor microbes on local and global cycling of carbon, nitrogen, phosphorus, sulfur and a host of other elements. More specific topics include (i) the role of microbes in many different processes, including alteration of igneous crust, diagenesis of marine sediment, formation and destruction of metalliferous deposits, formation and destruction of hydrocarbon deposits, (ii) the effect of microbes on the geochemistry of the subduction factory, and (iii) the influence of microbes on paleoceanographic records.

Drilling projects in the southwest Pacific will provide special opportunities to address most of these topics. Drilling in the Gulf of Papua provides one such opportunity, allowing for the close study of temporal variation and microbial influence in source-to-sink carbon cycling on a continental margin. It will also provide an excellent opportunity for examining the sensitivity of subseafloor ecosystems and biodiversity to glacial–interglacial change in sea level and tropical sedimentation. Another example is drilling in the Great Australian Bight, which will allow close examination of sulfur-cycling microbial communities in a large-scale subseafloor reflux–brine system (Wortmann et al., 2011). A third example is provided by southwestern Pacific subduction regions, including the Hikurangi Subduction Margin and the Tonga Trench, where the influence of subseafloor microbes on the geochemistry of the subduction factory can be examined.

## 2.3 Theme 3 – Earth connections: deep processes and their impact on Earth's surface environment

The southwest Pacific is one of the most active areas of the world in terms of the connections between deep processes and their impact on Earth's surface. Flows of material and energy among global reservoirs drive long-term changes in Earth's structure and composition, cause volcanism and tectonism, and create hospitable environments for the development and evolution of life. Plate tectonic processes have been eclipsed at times in Earth's history by episodes of massive magmatic outpourings in small areas, events that may occur when hot mantle ascends rapidly from great depth to erupt on Earth's surface, forming oceanic plateaus and continental flood basalts (so-called large igneous provinces, or LIPs). Within the southwest Pacific, the largest such LIP occurs with the Ontong Java Plateau (OJP, Fig. 2). The causes and environmental consequences of catastrophic magmatism forming large igneous provinces remain poorly constrained. Likewise, the processes that initiate new plate boundaries, a first-order problem in Earth dynamics, are poorly understood. At convergent plate boundaries, the initiation of subduction and formation of volcanic arcs remain enigmatic. The SW Pacific has a greater range of well-preserved subduction initiation events than anywhere else on Earth.

### 2.3.1 Formation of large igneous provinces and their impact on the global environment

The Ontong Java Plateau (Fig. 2) is the world's largest oceanic plateau and the most voluminous large igneous province on Earth. The implication is that the Greater Ontong Java Plateau volcanic event covered ~ 1 % of Earth's surface. The similar basalt chemistry and ages of eruptive episodes recorded by these constructs suggest a unique magmatic event in the history of Earth. Such a huge outpouring of lava during the initial constructional phase of the Greater Ontong Java Plateau is synchronous with the oceanic anoxic "Selli" event, suggesting a significant impact on ocean chemistry (Tejada et al., 2009). Large igneous province science would be advanced in five key areas through scientific ocean drilling: Obtaining deep sections within multiple large igneous provinces to examine magmatic (and therefore mantle source) variability through time; defining the nature of melting anomalies (which produce large igneous provinces); defining precise durations of oceanic large igneous province events; defining modes of eruption-constant effusion over several million years or several large pulse events over the same time interval; establishing relationships among oceanic large igneous provinces, oceanic anoxic events (OAEs), and other major environmental changes.

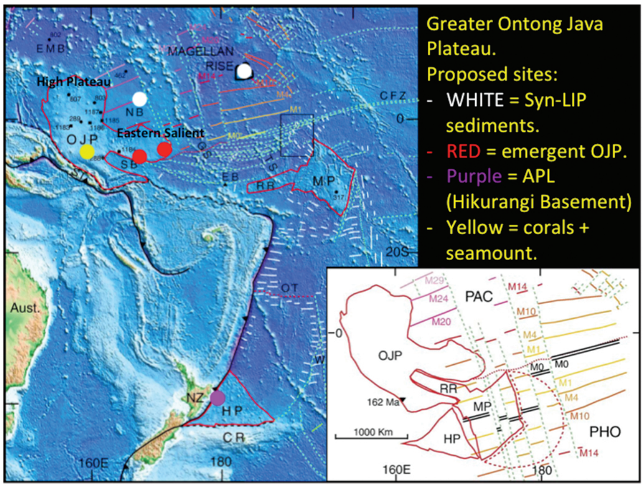

**Figure 2.** Present configuration of large igneous provinces (LIPs) in the SW Pacific (outlined in red) with proposed drilling sites. The inset shows reconfiguration of the Greater Ontong Java Plateau (OJP) suggesting the Ontong Java and Hikurangi (HP) plateaus and the Manihiki Plateau (MP) all formed during a single event adapted from Taylor (2006). Note: Robbie Ridge (RR), Ellis Basin (EB), East Mariana Basin (EMB), Nauru Basin (NB), Clipperton Fracture Zone (CFZ), Osbourn Trough (OT) and Chatham Rise (CR) are also shown. The inset shows a reconstruction at ~ 125 Ma prior to breakup and before Pacific (PAC) – Phoenix (PHO) spreading (from Taylor, 2006).

### 2.3.2 Structure and dynamics of mantle flow

Workshop participants discussed the scientific opportunities for further study of the Australian–Antarctic Discordance (AAD), as the region presents us with unique opportunities to address the IODP challenges concerning the composition, structure, and dynamics of Earth's upper mantle.

### 2.3.3 Initiation of subduction and origin of deep-water sedimentary basins

Subduction systems are the primary drivers of plate motions, mantle dynamics, and global geochemical cycles, but little is known about how subduction starts. What are the necessary initial conditions? How do forces and kinematics evolve? What are the short-term lithospheric consequences and surface signatures: vertical movements, deep-water sedimentary basins, convergence, extension, and volcanism? The southwest Pacific also provides an ideal opportunity to understand the process of large-scale subduction initiation because the Eocene onset of new subduction zones was accompanied by the most profound global reorganisation of tectonic plates since the late Cretaceous, and within the only part of Earth history with precisely known plate motions (Gurnis et al., 2004; Steinberger et al., 2004).

#### 2.3.4 832 Full: the Lord Howe Rise

The "Tasman frontier" is a sector of the southwest Pacific that lies between eastern Australia, western New Zealand, and New Caledonia (Fig. 1). Future ocean drilling in the Tasman Frontier (TF) is intriguing, because sedimentary records could address and several major challenges that relate to different themes, such as: how and why does subduction initiation occur? Did plate convergence precede and induce subduction initiation, or did it happen spontaneously? What vertical stresses occurred during subduction initiation? The magnitude and timing of uplift and subsidence across a broad region could be determined through drilling specific targets, ones that will enable evaluation and refinement of geodynamic models. Far-field uplift and subsidence, as strongly indicated from seismic stratigraphy, challenges existing geodynamic theory. Was regional bathymetry during the Palaeogene much different than it is at present? Proposed sites would target horizons that, from available seismic stratigraphy, suggest much of the Tasman Frontier was at or near sea level in the early Eocene, which would impact climate model simulations significantly. Did subduction initiation coincide with early Eocene warmth? How and why do Neogene oceanographic changes in the region relate to those elsewhere?

## 2.4 Theme 4 – Earth in motion: processes and hazards on human time scales

The southwest Pacific is one of the most active regions in the world in terms of the earthquake and volcanic events that frequently occur on human time scales. High-magnitude earthquakes and large volcanic eruptions reoccur at intervals of decades to centuries. Also other smaller events, such as slow-slip events and moderate eruptions, have even shorter repeat intervals that can be observed within a scientist's career. The sites of these events are prime targets for the ocean drilling program, where logging, coring and installing observatories in boreholes can be used to better understand dynamic processes such as the seismic and aseismic slip on megathrusts, the magmatic system under volcanoes, and the triggering of large landslides.

### 2.4.1 Hikurangi subduction margin IODP proposals to understand the origin of slow-slip event behaviour

Over the last decade, the discovery of episodic slow-slip events (SSEs) at subduction margins around the globe has led to an explosion of new theories about fault mechanics and subduction interface deformation mechanisms and rheology. The Hikurangi margin is the subject of three existing IODP proposals to "unlock the secrets of slow slip": 781-MDP (Multi-phase drilling project), 781A-Full (riserless drilling transect and observatories), and 781B-Full (riser drilling to intersect the slow-slip source area). The riser drilling proposal was a major topic of discussion at the workshop, and it was recently submitted to IODP in April 2013; the riserless proposal (781A-Full) has been forwarded by PEP to the JR facilities board with an excellent rating, and is awaiting ranking and scheduling. In addition to studies of slow slip, a number of other new ideas for using IODP drilling at the Hikurangi margin to understand gas hydrates and submarine landsliding processes were also developed and discussed at the workshop. We anticipate that some of these new ideas will be submitted either as APLs (Ancillary Project Letters) or full proposals in the future.

### 2.4.2 Global comparison of slip behaviour at the toe of subduction margin trenches

In the 2011 Tohoku $M_w$9.0 earthquake, the largest slip ($> 50$ m) occurred on the shallowest portion of the subduction thrust (Ito et al., 2011; Kodaira et al., 2012), which contributed greatly to the huge tsunami that followed the earthquake (Maeda et al., 2011). At the Nankai Trough, vitrinite reflectance studies of IODP cores from the shallow fault zone ($< 500$ m) suggest frictional heating and large, seismic slip close to the trench in previous megathrust earthquakes at Nankai (Sakaguchi et al., 2011). These new observations beg the question: do subduction megathrusts elsewhere commonly undergo large, seismic slip all the way to the trench? This is in stark contrast to the traditional view that the shallow megathrust is largely aseismic. A comparative study of shallow cores through the toe of many of the world's active subduction thrusts, including those in the southwest Pacific region such as the Hikurangi and Kermadec margins, is needed and would give us an excellent start in trying to gain a more comprehensive understanding of shallow megathrust seismic behaviour.

## 2.5 Theme 5 – marine resources: opportunities and responsibilities

The aim of this theme was to determine the contribution that IODP could make to the exploration, characterisation and responsible exploitation of marine resources in the southwest Pacific region. These resources might include offshore oil and gas, gas hydrates, and offshore minerals. There are additional opportunities to draw economic benefits from IODP participation: incorporating "marine resource" considerations into standard scientific proposals; developing targeted marine resource proposals in co-funding arrangements with government and industry (complementary project proposal, or CPP); commercial hire of IODP drilling vessels when they are in the region. Three areas were discussed:

### 2.5.1 Petroleum potential of the Lord Howe Rise

This is the largest submerged continent in the world and there are fundamental questions about its petroleum potential related to the largely unknown history and fabric of the rise. The rise contains a number of deep rift basins, with up to 6000 m of sediment, that are well characterised by seismic profiling but may or may not contain source, reservoir and cap rocks. Sparse stratigraphic information is limited to early DSDP wells (Legs 21 and 90). Potential exploration targets are believed to be Cretaceous, but only the uppermost Cretaceous (Maastrichtian) was reached in just two holes. Without basic stratigraphic information, the next stage in assessment of petroleum potential cannot be achieved and the pre-Maastrichtian geohistory cannot be determined.

### 2.5.2 Metal resource potential of southwest Pacific island arcs and back-arc basins

Many of the island nations of the southwest Pacific have limited land area with scarce mineral resources, but do have massive maritime territories with largely unexplored mineral potential. It is estimated that more than one million square kilometres of seafloor in the Asia–Pacific region is under mineral exploration license, providing researchers with an outstanding opportunity to leverage the often high-quality site survey data generated by mineral explorers to draft drilling proposals addressing fundamental scientific questions related to volcanology, crustal fluid fluxes, subduction input of volatiles into the oceans, and the limits and origin of life on Earth.

### 2.5.3 818-Pre: Brothers arc flux

The Brothers volcano has been extensively surveyed from surface vessels and submersibles. However, it lacks deep drilling, which is needed to understand its subseafloor hydrology and potential to form large accumulations of Cu-Au mineralisation. Two distinct hydrothermal systems of very different end-member chemical compositions exist within the same area, and drilling provides the opportunity to address scientific questions relevant to microbiology, volcanology, and the formation of significant ore bodies.

### 2.5.4 Manus Basin

The Manus back-arc basin lies at the convergent boundary between the major Indo-Australian and Pacific plates, and exhibits a complex tectonic history, including reversal of subduction due to the arrival of the Ontong Java Plateau at the old subduction zone. There are at least nineteen active sites of hydrothermal activity within the Manus Basin, making the area an ideal natural laboratory to investigate the controls on and inputs into ore forming processes on both a regional and a local scale.

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## Related Web Links

http://www.iodp.org/workshops
http://www.earthbyte.org/workshops/SWPacific_IODP/
http://www.iodp.org/Science-Plan-for-2013-2023/

Sci. Dril., 17, 51–59, 2014
www.sci-dril.net/17/51/2014/
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Scientific Drilling
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# The Japan Beyond-Brittle Project

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## 1 Introduction

### 1.1 Outline of the workshop

The international workshop “Japan Beyond-Brittle Project, JBBP – Scientific drilling to demonstrate the feasibility of engineered geothermal systems in ductile zones” was held at the Graduate School of Engineering, Tohoku University, Sendai, Japan, during 12–16 March 2013. The workshop was cosponsored by the ICDP (International Continental Scientific Drilling Program) and Tohoku University GCOE (Global Center Of Excellence) Project. A total of 102 people attended the workshop and 98 presentations were made (75 oral, 23 poster).

### 1.2 Background

Although various advantages of geothermal energy have been widely accepted, power generation using natural hydrothermal reservoirs has not been recognized in Japan as an attractive investment, mainly because of a general perception of high development risks and uncertain returns on investment.

An engineered geothermal system (EGS) is considered to be the best solution to the problems of the hydrothermal resources. However, previous Japanese hot dry rock (HDR) projects showed that water recovery from an EGS reservoir in a fracture-rich tectonic belt in Japan is at best 50 % (Tenma et al., 2004; Kaieda et al., 2005). Another important issue is the difficulty of designing EGS reservoirs in a tectonic-belt setting, where local variations in tectonic stress and fracture distribution are common. Furthermore, the occurrence of felt earthquakes from the EGS reservoirs (Majer et al., 2007; Häring et al., 2008) introduces additional environmental burdens and risks.

These problems in the development of hydrothermal and EGS reservoirs cannot be readily solved in Japan because they are intrinsically related to the physical characteristics and tectonic setting of the brittle rock mass. Hence,we initiated a project, the Japan Beyond-Brittle Project (JBBP), to investigate the feasibility of developing an EGS in brittle–ductile transition (BDT) zone. The expected advantages of EGS in the BDT are as follows:

1. More homogeneous rock properties and stress states in the BDT make it conceptually simpler to design and control geothermal reservoirs.
2. A nearly full recovery of injected water can be expected from hydraulically closed reservoirs.
3. Sustainable production can be realized by controlling the flow rate and chemical contents of circulated liquids.
4. Possible site-independent characteristics of ductile zones may lead to the establishment of universal design/development/control methodologies.
5. Induced/triggered earthquakes with damaging magnitudes will not occur in reservoirs in ductile rock masses.

**JBBP Reservoir (Type 1)**

Larger productivity and sustainability by connecting to deep HT hydrothermal system

Controlled quartz solubility for reservoir treatment and reduction of scaling

Lower cost relative to Type-2

**JBBP Reservoir (Type 2)**

Higher enthalpy

Nearly full water recovery

Universal design/development methodology

Possibility to reduce risk of large induced seismicity

Possible independency to existing hydrothermal resources for direct use

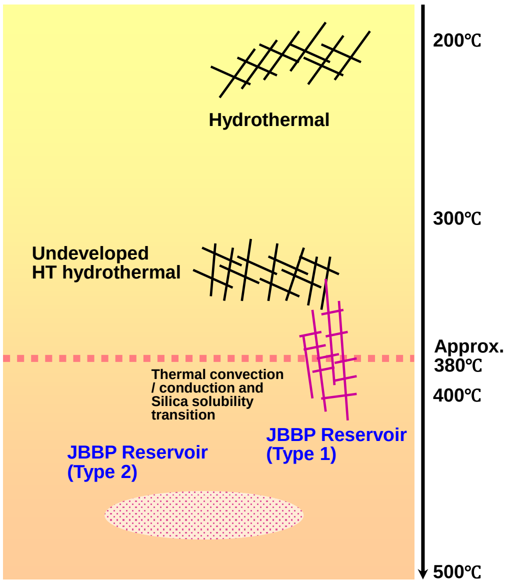

**Figure 1.** Two possible types of JBBP reservoirs.

## 2 Possible reservoir types for JBBP

It has concluded that there are two end-member reservoir models that should be considered (Fig. 1).

1. A JBBP type 1 reservoir would be created near the top of the BDT, where quartz solubility and fracture density are markedly different from those in the brittle zone. The reservoir should be connected to preexisting hydrothermal systems to increase productivity and provide sustainability.

2. A JBBP type 2 reservoir would be hydraulically or thermally created beyond the BDT, where preexisting fractures are less permeable, and would be hydraulically isolated from the hydrothermal system.

## 3 Characterization of the beyond-brittle rock mass

### 3.1 Current understanding of the characteristics of the beyond-brittle rock mass

The large strain rate by fluid injection renders the rock mass brittle because it fractures in tensile and shear modes, creating fractures aligned with the regional stress regime. These fractures are observed as millimeter- to centimeter-scale quartz veins in porphyry copper deposits, which are quartz-filled and plugged fractures, where quartz appears to have precipitated upon adiabatic decompression and cooling as fluids traversed from lithostatic pressure, $P$(l), to hydrostatic pressure, $P$(h), regimes. According to the experimental findings of Okamoto, Tsuchiya, and Saishu in the Tohoku University team, quartz precipitation at temperatures exceeding 400 °C seals permeability, possibly on a time scale as short as days or weeks.

The review above suggests that heat extraction from a 400 to 450 °C granite mass by hydrostatically pressured fluid injection will be challenging, especially because of fracture plugging by quartz and probably also because of closing of fractures by rock creep. Quartz fracture plugging can possibly be limited by high flow rates as fluid temperature descends to below 400 °C upon adiabatic decompression to $P < P$(h). Quartz precipitation rates may slow sufficiently at $T < 400$ °C to allow fluid ascent without the plugging of fractures. If not, there is a serious problem that requires investigation.

Rock physics experiments at high pressures and temperatures are central to the achievement of sustainable geothermal development. Characterization of the physical properties of rocks (e.g., permeability, $P$ and $S$ wave velocities, and electrical conductivity), is a strong indicator of the correct interpretation of the geophysical field data used for subsurface exploration.

Workshop participants suggested that laboratory-based physical investigations of the JBBP rock–fluid system should focus on fracture generation and the lifetime of fracture networks in ductile rock systems. Such studies will prove indispensable information for characterizing time and distance scales for fluid flow in ductile rocks and will also provide data that can be used to improve stimulation techniques in connection with new concepts of EGS beyond the brittle field.

### 3.2 Scientific challenges

Numerical simulation is an important technique that can be applied to assist in the realization of hydrothermal fluid flow in the beyond-brittle rock mass. Recent advances in numerical simulation techniques allow simulation of fully transient single- and multi-phase hydrothermal fluid flow on a continuum extending to magmatic conditions (Hayba and Ingebritsen, 1997; Coumou et al., 2008a, b; Weis et al., 2012). These simulations successfully reproduced a wide range of the key features of such systems (e.g., thermal structure and evolution, temporal and spatial patterns of fluid phase states, fluid pressure distribution).

A new approach to the characterization of deep rock masses may arise from the exchange of data and results. For example, in the new Swiss–Icelandic combined hydrological, geochemical and geophysical modeling of geothermal systems (COTHERM) project led by Thomas Driesner (Federal Institute of Technology, Switzerland), the capability of new simulation techniques to accurately predict the distribution of strongly varying fluid properties in the subsurface will be used to better calibrate interpretations of geophysical and geochemical signals. A similar technique could also be used in our project.

In the Kakkonda geothermal field (Japan), a geothermal drill hole (WD-1a; Fig. 2) penetrates the boundary between the hydrothermal-convection and heat-conduction zones (Doi et al., 1998); this is a unique example of drilling beyond the brittle rock mass. Drilling has shown that quartz solubility has a local minimum at ~ 3100 m depth (380 °C, 24 MPa), which is consistent with the depth of the hydrological boundary. Quartz precipitation has possibly created an impermeable siliceous layer at this depth. This water–rock interaction would lead to spontaneous development of the bottom of the hydrothermal-convection zone, which controls fluid flow.

In geothermal fields, we need to consider a coupled chemical and mechanical model to evaluate beyond-brittle geothermal reservoirs.

## 4 Creation and control of EGS reservoirs in the ductile zone

Although we know very little about the geometry of artificial or natural fracture systems in the BDT, we can speculate on the basis of two end-member scenarios. On one hand, hydraulic stimulation may produce a single fracture, or a zone of fracture deformation controlled by local stresses. On the other hand, a more complex cloudlike fracture network might be produced, where the geometry of the fracture system would depend on many factors. These could include deformation mechanisms, stresses, and rock properties. The natural systems of fluid flow can indicate the growth of such a fracture network, as shown by the movement of fluids or changes of pore pressure during and after stimulation. It is also possible that hydraulic fracturing could inadvertently trigger fault motion. Thus, it is very important to understand the mechanical characteristics of faults or fractures.

Our workshop discussions of the creation and maintenance of EGS reservoirs in the BDT and ductile zone were based on current knowledge, especially from the view point of rock mechanics. The subjects specified at the workshop as being of prime importance are (1) mechanical and hydraulic properties of rock, (2) in situ states of stress, and (3) seismic activity on fractures or faults.

### 4.1 Mechanical and hydraulic properties of rock

The creation and maintenance of such an embrittled zone embedded within a nominally ductile region in the deep crust poses significant scientific challenges. The first challenge is to understand how deformation, in the form of either tensile or shear fractures, can be nucleated in a matrix that will deform anelastically by, for example, cataclastic flow. The viscoelastic rheology and failure in such a transitional regime would likely involve a combination of semi-brittle mechanisms, including crystal plasticity, diffusive mass transfer, and microcracking. To formulate modeling methodology, it is advisable to take into account recent advances in the modeling of analogous geodynamic processes, such as stress relaxation during interseismic phases of the earthquake cycle.

It is of considerable importance to address coupled thermo-hydro-mechano-chemo (THMC) processes when considering the effective extraction of energy from geothermal reservoirs. Under high pressure and temperature conditions, chemical reactions such as mineral dissolution and precipitation are very active, and may quickly change the mechanical and hydraulic properties of host rocks. Therefore, the effects of the dissolution and precipitation kinetics on the physical properties of rocks should be examined microscopically.

### 4.2 In situ state of stress

Knowledge of the in situ state of stress and the geometry and hydrologic properties of potential failure surfaces (fractures, faults, and foliation) is required in order to create an EGS reservoir with optimal geometry, fracture density, and heat-extraction efficiency.

The magnitude of the least horizontal principal stress (SHmin) is best determined using small-scale hydraulic fracturing stress tests (minifracs). Owing to the difficulty of finding reliable open-hole packers for use at high temperatures, such tests are best carried out in geothermal wells by drilling a short (~ 20 m long) pilot hole from the bottom of cemented casing and pressurizing the cased hole to carry out a minifrac in the pilot hole. Ideally, minifracs would be conducted below every casing shoe during the drilling of a JBBP borehole, thus obtaining as complete a vertical stress profile as possible.

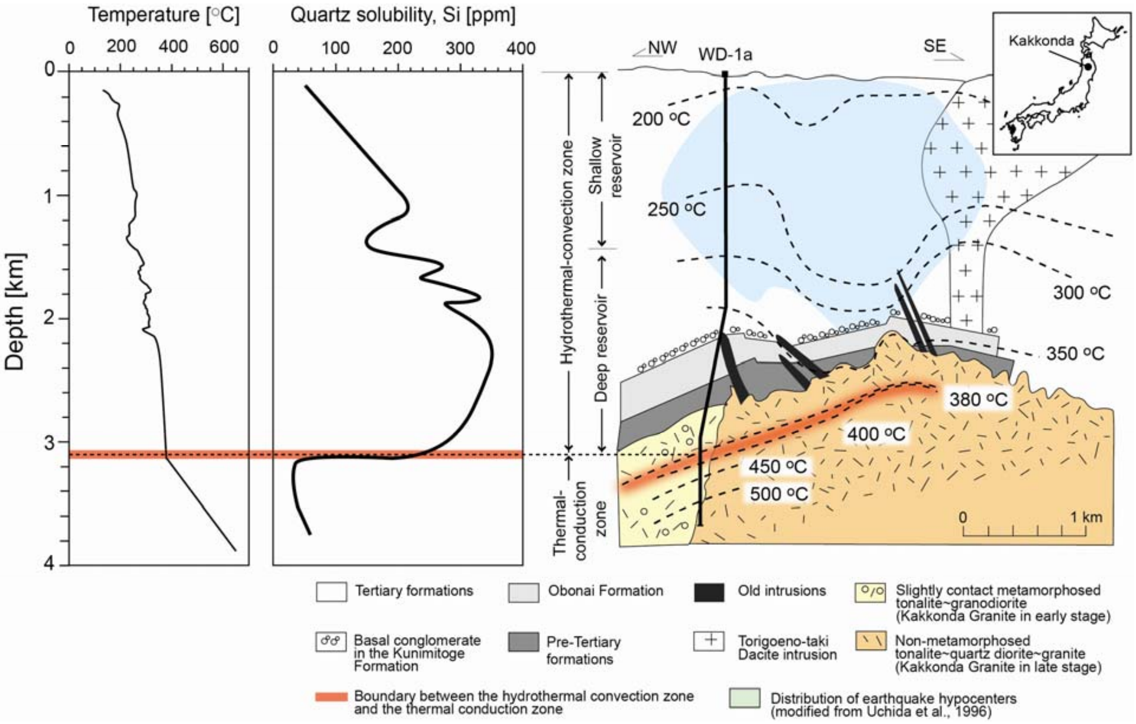

**Figure 2.** Location of the Kakkonda geothermal field in the Hachimantai volcanic field, northeastern Japan, and schematic cross section of the Kakkonda geothermal systems (modified after Doi et al., 1998). Well WD-1a encountered the boundary between the hydrothermal-convection and heat-conduction zones at a depth of 3100 m (Doi et al., 1998). This figure will be published by Saishu et al. (2014).

Acoustic and electrical borehole imaging tools can be used to determine the orientations of in situ principal stresses (through observations of breakouts and drilling-induced tensile cracks) as well as the distribution, orientation, and apparent apertures of preexisting natural fractures and faults. Image logs so acquired should be augmented with density logs to determine the vertical (overburden) stress, temperature–pressure-flow meter logs to identify preexisting permeable fractures and other fluid loss zones, and $P$ wave velocity logs to allow for in situ estimation of rock strength. The latter estimates are used to relate borehole breakout width to the magnitude of the greatest horizontal principal stress (SHmax) by using the magnitude of Shmin as measured during a minifrac test.

Below the brittle regime, preexisting fractures, if present, might have very low permeability and/or cohesive strength due to closure by plastic creep and sealing by secondary minerals. In such a case, it would be necessary to use higher fluid pressures to increase formation permeability through tensile failure. This could be augmented by extended circulation of cold fluids to lower the mean stress, creating a more pervasive, mixed-mode fracture network comprising both tensile and shear fractures. When a cold fluid is injected into a high-temperature rock, the fluid cools the rock locally around the injection borehole and fractures, and the cooling induces local shrinkage of the rock. Such shrinkage leads to a considerable reduction in the fluid pressures required for fracture initiation at the borehole wall, fracture extension, and the opening of fracture networks.

## 5 Geothermal exploration and monitoring of EGS reservoirs

### 5.1 Current status of technology

Temperature mapping is an essential component of geophysical surveys for EGS development. The use of aeromagnetic survey data to map depth to the Curie temperature isotherm is the only known way to directly detect temperature at depth. A spectral analysis method has been developed that assumes a fractal distribution of crustal magnetization; this method has recently been used to estimate depth to the Curie temperature at a potential EGS site in a continental environment.

Gravity surveys can provide information about the density distributions in subsurface rocks such as the massive granitic bodies that form EGS reservoirs. Modern gravimeters, such as the new superconducting gravimeter, can detect weak signals caused by fluid flow in deep reservoirs.

Because hydrothermal systems normally produce diagnostic resistivity anomalies, subsurface images produced from 3-D magnetotelluric data have shown reasonable agreement with borehole resistivity logs.

Monitoring of background seismic activity during the predevelopment phase of an EGS project is necessary in order to understand preexisting seismicity at the site. Hasegawa (2009), Imanishi et al. (2011a, b); Ma et al. (2012) and Schwartz and Rokosky (2007) showed various characteristics of seismic events which occurred beyond the BDT.

### 5.2 Technological challenges for detecting suitable targets and monitoring developed reservoirs

Recently developed 3-D repeated aeromagnetic survey techniques might be useful for estimation of deep magnetic structures related to hot dry rocks.

Recent advances in gravity survey technology, especially the development of new superconducting gravimeters, allow for the detection of small changes in the gravity field that are caused by mass movements or the redistribution of fluids in geothermal reservoirs.

Resolution at depth is inherently low in surface magnetotelluric survey data. To increase resolution, high-resolution surveys (such as cross-hole or borehole–surface electromagnetic surveys) should be conducted close to the reservoir.

### 5.3 Current understanding of induced seismicity associated with fluid injection and production at an EGS

The hypocenters of large induced seismic events are usually within the central region of the seismic cloud or near its boundary. The source radii are comparable to or smaller than those of the hypocentral cloud (Asanuma et al., 2005, 2011; Mukuhira et al., 2013), suggesting that the size of the rupture is restricted by the dimensions of stimulated zones in an EGS. Pore pressures determined at the time of occurrence of large induced events has shown that fractures were not critically stressed then (Asanuma et al., 2012; Mukuhira et al., 2013; Terakawa et al., 2012). The observation that many large induced events have occurred after shut-in and bleeding-off indicates that reservoir pressure or stress state is redistributed as a result of the cessation of fluid flow.

### 5.4 Expectations of induced seismicity for JBBP

The reservoir required to extract thermal energy in the order of 10 MW would be of dimensions in the order of several hundred meters; seismic events of moment magnitude 4–5 can be caused. However, if the reservoir is connected to an existing fracture system above the BDT (JBBP type 1 reservoir), the risk of large induced seismic events increases.

### 5.5 Challenges for prevention of large induced seismicity in and around the JBBP reservoirs

Dynamic THMC modeling of the reservoir and surrounding zones of the JBBP reservoir presents a challenge. Investigation of methods of reservoir creation such that large induced events are suppressed should be undertaken by integrated geomechanical modeling that deals with all of these factors.

## 6 Engineering development

### 6.1 Current status of related technologies

JBBP reservoirs will be created at depths of 3–5 km where formation temperatures are 350–500 °C and formation pressures are 30–50 MPa. Experience gained during the drilling of well WD-1a at the Kakkonda geothermal field (Muraoka et al., 1998) suggests that fluids of high salinity and HCl content may be present. Functioning in conditions such as these is beyond the capability of most currently available off-the-shelf technology.

#### 6.1.1 Current status of drilling and well completion technology

1. The top drive system (TDS), which can continuously cool a borehole, enables penetration of rock masses at temperatures exceeding 500 °C at Kakkonda (Saito et al., 1998).

2. In the IDDP (Iceland Deep Drilling Project), the drilling was delayed because of thermal cracking, hole collapse, and magma quenching to glass near/inside the magma body. Magma has also been intersected during drilling of injection well KS-13 in Hawaii (Teplow et al., 2009).

3. Well design may need to be revised to deal with supercritical fluids – in particular, to avoid steam explosions in the casing annulus by HCl, $H_2S$, $CO_2$, and possibly HF. Recent corrosion and scaling experiments by IDDP-1 and the Salton Sea Project indicate that INCONEL®alloy 625, titanium grade 7 and Beta-C titanium casing performed well (Ragnarsdóttir, 2013; Love et al., 1988).

4. Collection and recovery of spot-core samples from a high-temperature environment can be problematic (e.g., Lutz et al., 2012). An alternative approach is to use a hybrid drilling rig that can switch from rotary drilling to continuous wireline coring (e.g., Furry et al., 1996). Successful coring was achieved at high temperatures in IDDP wells by using a corer provided by Alister Skinner.

5. The cement commonly used to set casing can withstand temperatures up to about 400 °C. For the WD-1a well, casing was cemented at a formation temperature of around 360 °C (Saito et al., 1998). Halliburton is developing a high-temperature cement (ThermaLock™) that can be used at formation temperatures up to 538 °C.

6. A bentonite- and water-based, low-solids, low-density mud was used with a high-temperature dispersant (G-500S) in the Kakkonda WD-1a well. Telnite Co., Ltd.

(Tokyo, Japan) now provides a Hypergel/G-500S high-temperature mud system. M-I SWACO (part of the Schlumberger group) can also provide high-temperature water-based muds usable at temperatures above 260 °C.

7. A research and development project funded by the US Department of Energy to develop a high-temperature (300 °C) directional drilling system is being undertaken by Baker Hughes.

### 6.1.2 Expectations for drilling and well completion for JBBP

1. The borehole will need to be effectively cooled to below 160 °C during normal TDS drilling operations. Casing and cementing under extreme high temperature subsurface conditions should be possible if cooling of the borehole during TDS drilling is sufficient.
2. There will be risk of the buckling or breaking of casing pipe and the destruction of the cement sheath in response to the thermal stress induced by injection during the circulation of cool liquid into the high-temperature borehole. Corrosion of the casing pipe and wellhead may also occur.
3. Drilling of a highly deviated borehole into the BDT to create subvertical reservoirs of sufficient thermal capacity will be difficult.

### 6.1.3 Current status of stimulation and injection technology

1. Many EGS reservoirs have been created by full-hole pressurization, either by pressurizing the entire open-hole section (Häring et al., 2008), or by isolating the open-hole section using casing packers.
2. The maximum operating temperature of the Halliburton RTTS®tool and inflatable packers is 180–190 °C. An alternative for zonal isolation during reservoir stimulation is the use of chemical diverters, which have been successfully deployed by the Newberry EGS project in Oregon, USA (e.g., Petty et al., 2013).
3. Multistage hydraulic fracturing equipment has been deployed in recent shale gas developments in North America, although in a relatively low-temperature environment. The stability and behavior of fracturing fluids and proppants under high-temperature conditions are poorly understood.

### 6.1.4 Expectations for stimulation and injection for JBBP

1. Multilevel stimulation to investigate changes in the response of the BDT rock mass with increasing depth should be undertaken within JBBP. A multilevel fracture system would be expected to increase the extent of fracturing for heat exchange. However, no packers that can be used under conditions expected in the BDT are currently commercially available.

### 6.1.5 Current status of logging and sampling technology

1. Most of the logging tools used in the oil industry can be operated at temperatures up to 175 °C. Some high-temperature (HT) pressure-temperature-spinner (PTS) tools can be used in memory mode at 400 °C on a slickline, whereas temperature, televiewer, and spectral gamma tools can be operated at up to 300 °C on a wireline. The maximum operating temperature for HT logging-while-drilling (LWD) tools is 230 °C.
2. The maximum operating temperature for a standard seven-core wireline cable is 315 °C; a slickline cable can be used at temperatures exceeding 400 °C.
3. The ICDP (International Continental Scientific Drilling Program) provides online monitoring of gas (OLGA) during drilling to extract and analyze gases ($N_2$, $O_2$, $CO_2$, $CH_4$, Ar, He, $H_2$, $C_1$–$C_4$, $^{222}Rn$) from the circulating drilling mud. This technique has been successfully used in several ICDP projects (San Andreas Fault Observatory at Depth; Unzen, Japan) and IODP (International Ocean Discovery Program) riser drilling expeditions (e.g., Expedition 319) (e.g., Erzinger et al., 2006).
4. A downhole sampler was developed by Lysne et al. (1997) and by NEDO (New Energy and Industrial Technology Development Organization) (Sato et al., 2002). Thermochem Energy Consulting & Chemical Testing has continued with the development of a two-phase high-temperature (to 400 °C) downhole sampler.
5. Metal-coated optic fiber designed for industrial and telecommunications use is thermostable up to 600 °C, although cable length is limited to several tens of meters.
6. Most commercially available high-temperature electronic apparati, fabricated with silicon-on-insulator (SOI) technology, are limited to a maximum operating temperature of 225 °C (a few to 300 °C).
7. Wider band gap (WBG) materials such as silicon carbide (SiC) must be utilized for the fabrication of HT sensors and circuits (Azevedo et al., 2007).

### 6.1.6 Expectations for logging and sampling for JBBP

1. It will be possible to collect information about the BDT rock mass by LWD, although there are risks of thermal damage to downhole tools.

2. Most of the existing logging tools can be run during or immediately after periods of circulation, at which times the borehole temperature will not have returned to its initial state.

3. Although operating times will be restricted, PTS tools can be used in memory mode during the stimulation and circulation phases. For thermal power monitoring, pressure and temperature tools will need to access the well for the full range of expected temperatures and pressures.

### 6.1.7 Current status of technology for EGS reservoir maintenance

1. Reservoir productivity is maintained by injection, pressure build-up, and stimulation.

2. Scaling is avoided via the acid treatment of injection fluids.

3. Scaling within heat exchange apparatus has been observed at Soultz (Scheiber et al., 2012).

### 6.1.8 Expectations for maintenance of the JBBP reservoir

1. The solubility of quartz will change drastically in the BDT, causing channeling and shortcut flow paths as a result of the solution and precipitation of quartz within the JBBP reservoir.

### 6.2 Technology developments required for JBBP

1. Drilling technologies: The risks and costs of drilling and well completion should be reduced as much as possible. Methods of well completion and materials used for casing and cementing that will allow long-term production and injection for JBBP reservoirs should be investigated. Coring equipment and operations should be developed that overcome the inadequate downhole cooling during coring operations.

2. Monitoring technology: fiber optic distributed sensing (e.g., distributed temperature sensing (DTS) + distributed acoustic sensing (DAS)) should be used to monitor and evaluate the stimulation treatment. Technologies to delineate the structure of the fracture system and the distribution of permeability should be developed. New survey methods (e.g., surface-borehole combination) and inversion theories (e.g., focused inversion) will be useful in identifying drilling targets and monitoring JBBP reservoirs. Highly sophisticated tracer methods (e.g., smart tracer) in combination with 3-D/4-D inversion theory have promise for reservoir monitoring.

3. Reservoir creation and maintenance technology: the use of proppants and appropriate fracturing/stimulation liquids should be investigated. Technologies that enable the avoidance or control of channeling and shortcut flow paths is of critical importance for sustainable production.

4. Zonal isolation technology: technology to isolate openhole sections at formation temperatures of up to 450 °C should be developed to allow for the creation of multilevel thermally productive reservoirs.

5. Logging and borehole testing technologies: high-temperature logging tools that can operate at 450 °C are needed to understand the properties of the beyond-brittle rock mass and fracture system. A technique to measure or estimate in situ stress at beyond-brittle depths is of critical importance in the JBBP.

## 7 Contribution of JBBP to Earth sciences

The JBBP will directly contribute to a broad range of earth science disciplines. We expect that the information so derived from core analyses and bore hole tests can be effectively used to improve our understanding of phenomena such as dehydration/degassing of magmas, global hydrogeology in the Earth's crust, and the processes by which hydrothermal convection/conduction zones can be created. Laboratory tests on fracturing in rock specimens at high temperatures and pressures as well as the testing and monitoring of deep boreholes can provide information on the dynamic response and stress state of the rock mass beyond the BDT, which will lead to improved scientific understanding and interpretation of the mechanics of earthquakes at depth. New exploration technologies applied to identify the BDT will contribute to our ability to determine the thermal and structural characteristics of phenomena such as volcanoes and seismogenic zones in the Earth's crust.

## 8 Roadmap and implementation plan

Two-and-a-half years of lead time might be required before submission of a full drilling proposal to ICDP (Fig. 3). This lead time will be used to further our scientific understanding of the beyond-brittle rock mass, develop the new technologies, undertake surveys of possible sites, and develop a drill program and contingency plans.

A number of current geothermal projects target supercritical fluids in shallow, still-hot, molten igneous intrusions in young volcanic rocks along plate boundaries and at hot spots. These include established geothermal fields in Iceland, New Zealand, the Philippines, Indonesia, Italy, and the United States. International collaboration, particularly with ICDP high-temperature geothermal projects worldwide, is of

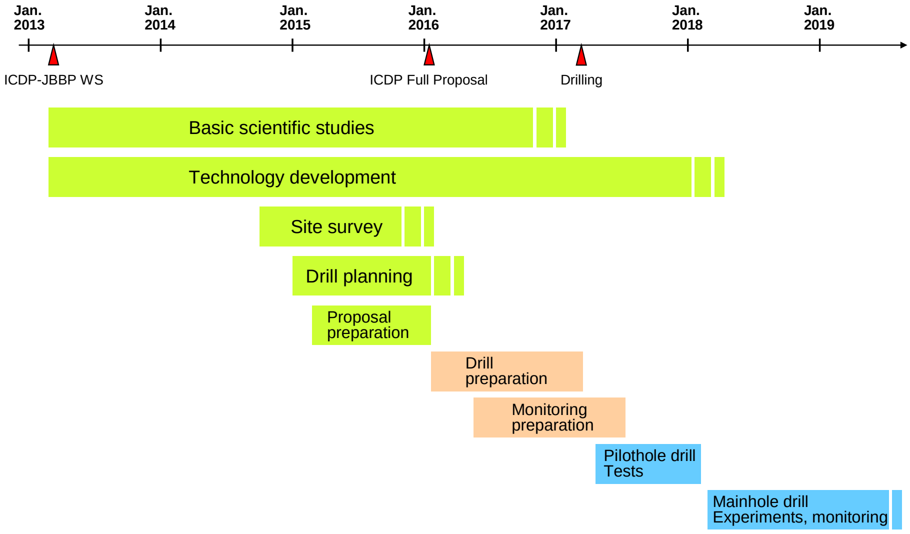

**Figure 3.** Roadmap for the development of the full JBBP proposal and subsequent drilling.

critical importance for success of the JBBP, as it will allow for the sharing of scientific knowledge and technology.

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# IODP Deep Biosphere Research Workshop report – a synthesis of recent investigations, and discussion of new research questions and drilling targets

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**Abstract.** During the past decade, the IODP (International Ocean Discovery Program) has fostered a significant increase in deep biosphere investigations in the marine sedimentary and crustal environments, and scientists are well-poised to continue this momentum into the next phase of the IODP. The goals of this workshop were to evaluate recent findings in a global context, synthesize available biogeochemical data to foster thermodynamic and metabolic activity modeling and measurements, identify regional targets for future targeted sampling and dedicated expeditions, foster collaborations, and highlight the accomplishments of deep biosphere research within IODP. Twenty-four scientists from around the world participated in this one-day workshop sponsored by IODP-MI and held in Florence, Italy, immediately prior to the Goldschmidt 2013 conference. A major topic of discussion at the workshop was the continued need for standard biological sampling and measurements across IODP platforms. Workshop participants renew the call to IODP operators to implement recommended protocols.

## 1 Introduction to Deep Biosphere Objectives in IODP

Scientific ocean drilling is entering its 48th year and is poised to continue creating momentous breakthroughs in the understanding of Earth processes. Four challenges have been set forth by the drilling community as the best opportunities for rapid achievement of transformative science: climate and ocean change; Earth connections; Earth in motion; and biosphere frontiers (IODP, 2011). Interdisciplinary science has been the foundation of the drilling program, and recently deep biosphere science has been recognized as a significant contributor in addressing questions across all themes, particularly climate and ocean change. It was specifically noted during the 2012 Building US Strategies Workshop that many scientists who do not directly identify their research as relevant to biosphere frontiers are nevertheless interested in biosphere challenges and would sail, request data, or apply others' results to their research. The priorities within biosphere frontiers challenge address questions such as *What are the origin, composition, and global significance of subseafloor communities? What are the limits of life in the subseafloor? How sensitive are ecosystems and biodiversity to environmental change?*

Several IODP (International Ocean Discovery Program) expeditions have focused on testing specific hypotheses regarding factors that control the distribution, community composition, and activities of the deep biosphere in a diverse array of subseafloor environments. These environments included a near-shore upwelling regime (Expedition 201: Peru Margin), extremely low-energy sediments (Expedition 329: South Pacific Gyre and Expedition 336: North Pond), oceanic crust (Expeditions 301 and 327: Juan de Fuca Ridge, and Expedition 336: North Pond), near-hydrothermal vents (Expedition 331: deep hot biosphere), a carbon-rich environment (Expedition 337: deep coalbed biosphere off Shimokita), and, most recently, the Baltic Sea paleoenvironment (Expedition 347). These expeditions demonstrate the rapid growth of deep biosphere research and the critical contributions provided by scientific ocean drilling. They also highlight the fact that deep biosphere investigations are not platform-specific, but can be adapted for IODP expeditions on the RV *JOIDES Resolution*, RV *Chikyu*, or on mission-specific platforms. These recent advances and expeditions prompted a call for a workshop to synthesize new findings in a global context, and to identify obstacles to new discoveries.

## 2 Recent deep biosphere discovery highlights

Since the incorporation of sterile sampling techniques in 2001, ODP (Ocean Drilling Program) and IODP expeditions have produced a wealth of high-impact discoveries about the subsurface biosphere. The largest leap forward was simply the discovery that microorganisms (archaea and bacteria) are present, intact, and metabolically active in uncontaminated deep subsurface sediments (Parkes et al., 2005; Schippers et al., 2005; Biddle et al., 2006; Morono et al., 2011). Not only are they present, but also they are taxonomically diverse, and include many new deep evolutionary branches on the tree of life (Schippers et al., 2005; Biddle et al., 2006; Inagaki et al., 2006). The growing library of deep subsurface sedimentary cell count measurements has enabled the most refined estimate of the total amount of subsurface life to date, showing this vast ecosystem to rival the microbial biomass of all the oceans (Kallmeyer et al., 2012). More recent IODP expeditions have given the first glimpses into life in sediments with very low deposition rates and with little access to photosynthetically derived detrital food sources. Small populations of slowly metabolizing microorganisms nonetheless continue to drive diagenetic processes in these extremely harsh environments (D’Hondt et al., 2009; Røy et al., 2012). These findings represent a major breakthrough in our understanding of how life can be sustained by alternative energy sources, possibly fueled by the radiolysis of water (Blair et al., 2007). Life, therefore, is not forced to conform to the energy-rich habits provided by surface photosynthetic conditions. Other IODP expeditions have shown that life exists in the subseafloor oceanic crust (Mason et al., 2010; Lever et al., 2013), suggesting that samples from even deeper below the subfloor will yield countless new discoveries.

With only a handful of microbiology-based drilling expeditions to date, subseafloor microbiology and biogeochemistry studies have made transformative discoveries that have added a new level of understanding to biological and chemical oceanography. Active microbial metabolism in the subseafloor is now known to proceed over geological timescales (D’Hondt et al., 2002, 2004; Orcutt et al., 2011; Lomstein et al., 2012; Lever et al., 2013), in sediment that is up to 86 million years old (Røy et al., 2012). Genomic, metagenomic and metatranscriptomic data sets from the subseafloor have allowed for metabolic rate calculations and measurements to be placed in a microbiological context (Biddle et al., 2008; Mills et al., 2012; Lloyd et al., 2013; Orsi et al., 2013b). New techniques for assessing the activity and whole genomic material from individual microbial cells have opened up the possibility of discovering new capabilities in living native subsurface cells (Morono et al., 2011; Lloyd et al., 2013), and by employing new chemical indicators for sporulated cells, researchers now have the tools to distinguish between dormant and metabolically active populations (Lomstein et al., 2012). Finally, the third domain of life, Eukarya (specifically fungi), is also now known to be active in the subseafloor and, likely, to play an important role in the degradation of organic matter in subseafloor sediment (Biddle et al., 2005; Edgcomb et al., 2011; Orsi et al., 2013a). Such studies have fostered a new level of understanding of subseafloor microbiology and have laid the foundation for future investigations of important subseafloor microbial processes.

## 3 Using geochemical and geophysical data to constrain microbial activity

Although the ubiquity of active microorganisms in marine deep sediments has been confirmed, it is not yet clear exactly what they are doing or how fast they are doing it (Jørgensen, 2011). One approach to constraining answers to these questions is to use quantitative models that employ the physical and chemical data that describe sedimentary ecosystems. For example, temperature, pressure, and compositional information reported for particular environments can be combined with thermodynamic data to calculate the amount of energy available to microorganisms in sediments, and from what reactions this energy comes. The hypothesis guiding these calculations is that the reactions that are the most energy-yielding in a particular environment are most likely to be catalyzed by resident microorganisms. These kinds of calculations have been carried out to varying extents in deep-sea sediments located in the Bay of Bengal (Schrum et al., 2009), Guaymas Basin, and the Black Sea (LaRowe et al., 2008), Peru Margin (Biddle et al., 2006; Wang et al., 2010; LaRowe and Amend, 2014), the Gulf of Mexico (Joye et al., 2009), the South Pacific Gyre (LaRowe and Amend, 2014), the Juan de Fuca Ridge (LaRowe and Amend, 2014), and the Juan de Fuca Ridge flank (Lever et al., 2010). In a related study, the energetic potential of iron and sulfur-bearing minerals from a number of DSDP/ODP drill sites was also quantified (Bach and Edwards, 2003). The limitation of this thermodynamic approach is that the results of these calculations only reveal the amount of energy that is available from the reactions for which there are sufficient chemical data, and nothing is determined about whether these reactions actually occur, and, if so, at what rates.

A complementary approach to understanding microbial behavior in the deep biosphere utilizes reaction-transport models (RTMs) that relate depth-dependent compositional trends observed in sediments to the rates of diffusion, advection and abiotic and microbially mediated reactions. Although RTMs have been applied to explain the driving forces shaping numerous ecosystems, few have been used to quantify the activity of microorganisms in marine deep sediments. Notable exceptions include models applied to sediments from the Demerara Rise (Arndt et al., 2006) and the eastern equatorial Pacific (Wang et al., 2008). A RTM has recently been applied to quantify the rates of microbial catabolism in deep-sea hydrothermal vent chimneys (LaRowe et al., 2014), and similar types of models were used to constrain oxygen consumption patterns in upper oceanic crust (Orcutt et al., 2013) and North Pacific Gyre (Røy et al., 2012). Both bioenergetic and RTM strategies for understanding the deep biosphere functions are restricted by the availability of physiochemical data produced by the IODP. However, as more IODP sites are microbiologically characterized, the resulting physiological and biomolecular data can be used in a complementary fashion with modeling techniques. The archiving of geochemical data in databases such as SEDIS (Scientific Earth Drilling Information Service) is critical for these types of models, and archival of related microbiological data in common databases should be a priority for the deep biosphere community. Importantly, it is clear that deep biosphere scientists need to work closely with scientists from other disciplines, such as geophysics and geochemistry, to assemble and understand the environmental conditions and constraints on microbial activity.

## 4 On the horizon

Future studies of subseafloor microbiology will build upon IODP's foundation by taking advantage of the rapid evolution in DNA and RNA sequencing technology, e.g. the "genomic revolution". The average cost of sequencing a bacterial genome is now under USD 1000, one million bases of DNA data can be obtained for less than USD 1, and sequencing technologies are continuously improving. Furthermore, advances in preservation methods for biological material, such as the new sampling freezing technologies, promise to greatly enhance recovery of DNA, RNA, and other biomolecules from cryogenically frozen samples. These genomic approaches are appealing due to the high throughput and high data : cost ratio, but they only truly become relevant and potentially transformative when paired with biogeochemical measurements and models of important microbial processes (e.g. carbon oxidation rates, oxygen/nitrate/iron/manganese/sulfate reduction rates, methanogenesis, and organic matter remineralization). Moreover, because the cost of DNA sequencing is no longer the rate-determining step for DNA- and RNA-based studies, careful consideration of sampling design should be made when studying the spatial ecology of subseafloor microbes. For example, it is now possible to easily barcode and sequence hundreds of samples in parallel, obtaining hundreds of thousands of DNA sequence reads for each sample. Thus, microbial ecologists can now produce biological replicates, and scale up the sampling efforts for spatially relevant studies. The rate-determining step for DNA and RNA sequence-based studies has shifted from data production to data analysis. Innovative methods will need to be developed to get the most out of sequence databases to use them to their maximum advantage, and to use genetic information to catalyze new hypotheses for direct testing in the hard-to-reach subsurface ecosystem. This is an exciting time because microbial ecology studies can now utilize sampling designs and scales similar to those used in more traditional fields of ecology (e.g. botany and zoology), to reach a deeper level of understanding of subseafloor microbial ecology and of how distributions and activities are linked to in situ geochemistry and geology across different subseafloor provinces.

Furthermore, there is increasing awareness that efforts to enrich and cultivate rare and dominant deep biosphere species are needed in order to understand growth rates and adaptation strategies for members of the marine deep biosphere. The increasing sophistication of laboratory assets on the RV *JOIDES Resolution* and RV *Chikyu* for enabling shipboard cultivation and microbiological studies has greatly enhanced these efforts, and more developments in this area would be beneficial. Cultivation efforts on mission-specific platforms are somewhat limited, however, due to limited suitable laboratory space and equipment for such work.

## 5 Recommendations

The potential for major discoveries in the field of subsurface biogeochemistry/microbial ecology is significant given the large number of active early-career researchers, the prominence of research objectives within the new IODP 10-year science plan, and large organizations dedicated to deep biosphere research, including the Center for Dark Energy Biosphere Investigations (C-DEBI, funded by the US National Science Foundation) and the Deep Carbon Observatory (funded by the Sloan Foundation). The enthusiasm of early-career researchers in this field was demonstrated

**Figure 1.** Participants in the IODP Deep Biosphere Workshop at the Grand Hotel Baglioni in Florence, Italy, on 25 August 2013. Not pictured: Steve D'Hondt, Kai-Uwe Hinrichs.

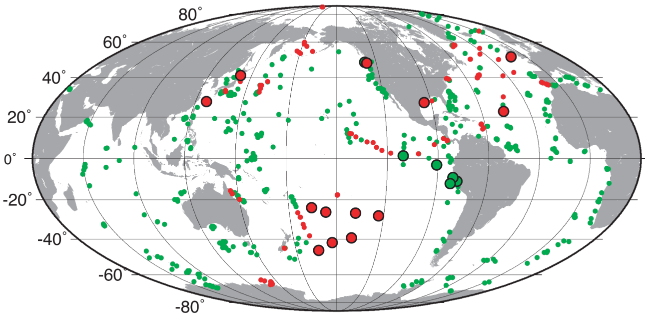

**Figure 2.** Combined ODP (green circles) and IODP (red circles) drill sites map. Larger symbols show sites where a complete and well-documented microbiological sampling campaign was adopted. For reference, these are sites 1225–1231, 1244, 1245, 1249–1251, C0013–C0016, C0020, U1301, U1316–1318, U1320, U1324, U1362, U1365–U1371, and U1382–U1384.

during the IODP Deep Biosphere Research Workshop, in which the participants recognized the immediate importance of establishing standardizing routine contamination testing of core material, sampling core material at regular intervals for archival storage, and immediately performing cell counts during shipboard operations. While deep biosphere research builds on a rich history of biogeochemical studies within ODP–IODP, from over 800 sites drilled during the course of the ODP–IODP programs, only 31 sites (during 10 expeditions) have been properly sampled, documented and archived for multiple microbiological assays, such as DNA extraction, cell counts, and cultivation studies (Fig. 2). Despite this small percentage of sites, the large number of transformative discoveries in deep biosphere research resulting from these samples is remarkable; only a few of the notable papers are listed at the beginning of this report. Thus, continued and additional microbiological sampling on future drilling expeditions is likely to result in even more transformative research on deep life. The proper collecting, processing and preserving of core material using biologically sensitive techniques was seen as essential to ensure adequate access of samples to both the shipboard and shore-based scientists. Several long-term goals were also discussed, including the identification of a common nucleic acid extraction protocol and the selection of specific genes/primers for targeted molecular characterizations. We determined that future discussions with a broader audience would be required to establish these standards. However, success in establishing such protocols should be considered a high priority, as they will facilitate the construction of data sets comparable between expeditions and provide the needed linkage between individual efforts made by our growing community.

During workshop discussions, it was noted that similar recommendations for standard and routine sampling, additional archived resources, and advanced training of technicians have been presented to IODP and ship operators in the past without full implementation (for example, SPC (Science Planning Committee) Consensuses 808–10, 808–11, 808–12, and 808–15). Therefore, for the success of future biosphere explorations, a revised recommendation from the subsurface community, including new techniques and technologies, should be crafted and presented to coincide with the start of the new International Ocean Discovery Program. To facilitate biological sampling and processing, advanced training of current technicians or ideally a microbiology-specific technician sailing on each expedition will be recommended. While all of these recommendations represent a substantial step forward, it is noted that in the new science plan, a quarter of the objectives are directly associated with biological research, with many of the other objectives reliant upon biological data. We must, therefore, strive for implementation of our new plan for biological exploration. The involvement of the NSF (National Science Foundation), along with IODP directors, curators, and technicians, is seen as the best course of action. Efforts are underway to complete this task, with a formal recommendation scheduled as early as 2014.

## Workshop participants

Jan Amend (coorganizer), Heath Mills (coorganizer), Beth N. Orcutt (coorganizer), Karine Alain, Marco Blöthe, Steve D'Hondt, Jiasong Fang, Gretchen Früh-Green, Kai-Uwe Hinrichs, Tatsuhiko Hoshino, Akira Ijiri, Fumio Inagaki, Yusuke Kubo, Jessica Labonte, Doug LaRowe, Karen Lloyd, Yuki Morono, Bill Orsi, Brandi Kiel Reese, Susumu Sakata, Justine Sauvage, Axel Schippers, Fengping Wang, Xiang Xiao.

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## DOSECC Returns to its Roots

DOSECC (Drilling, Observation, and Sampling of Earth's Continental Crust) returns to its roots as a non-profit research consortium to promote and facilitate continental scientific drilling.

DOSECC was originally developed as a University consortium with a mission to provide leadership and technical support to continental scientific drilling projects. Through time, DOSECC evolved and was charged with maintaining a continent drilling facility to provide scientific drilling expertise to principal investigators, design and implement new tools and platforms, and manage scientific drilling projects. These duties have now shifted to the new U.S. Continental Scientific Drilling Coordination Office at LacCore. As a result of these changes, DOSECC has transferred its drilling facilities in a managed process that will maintain drilling equipment for use by the scientific community. The Deep Lake Drilling System (DLDS) has been sold to the International Continental Drilling Program (ICDP), and DOSECC's for-profit subsidiary, DOSECC Exploration Services (DES), has been sold in a structured management buy-out to Geoscience Technology and Engineering, which will continue to provide drilling services to the scientific community including operations of the DLDS.

DOSECC will now operate solely as a non-profit research consortium to represent the scientific drilling community. We are looking forward to working with the new U.S. CSD Coordination Office as the voice of continental drilling.

**John Shervais (President) and James Russell (Chairman of Board)**

## Scientific drilling at EGU and ISC 2014

During spring and summer 2014, ECORD and ICDP will organise joint activities and events at two major conferences to promote ocean and continental research drilling.

At the EGU General Assembly 2014 in Vienna, Austria, from 27 April to 1 May, the IODP-ICDP exhibition booth (#55-56-57) will be a meeting point for everyone looking for news and information about the programmes. The "EuroForum 2014 – Major achievements and perspectives in scientific ocean and continental drilling", a co-organised science session with talks and posters, will be held on Tuesday 28 April. Then the IODP-ICDP Townhall Meeting will be the place to share our views on recent and future exciting challenges of the programmes. In co-ordination with the EGU Press Office, ECORD organises a media conference "Looking into the past to predict future climate: new results from the IODP Baltic Expedition on Tuesday 28 April at 14:00.
More detailed information with links is posted on http://www.ecord.org/pi/egu14.html.

For the first time ECORD and ICDP will present ocean and continental research drilling programmes at the 19th International Sedimentological Congress (ISC) from 18 to 22 August 2014, in Geneva, Switzerland (http://www.sedimentologists.org/meetings/isc). A joint exhibition booth (#12) will be organised in conjunction with IODP and ICDP science sessions. Detailed information will be posted soon on the ECORD and ICDP websites.

We look forward to meeting you in Vienna and Geneva!

**Patricia Maruéjol, ECORD**

## A new Science Plan for ICDP

"Imaging the Past to Imagine our Future" is the motto for future science in the ICDP. About 180 geoscientists, stakeholders, representative from partner programs, early career scientists, policymakers, and industry professionals from 26 countries gathered at the ICDP Science Conference 2013 (11–14 Nov, Potsdam, Germany) and discussed the forthcoming ICDP Science Plan. It will broaden the goals of continental scientific drilling towards targeted understanding of geoprocesses in relation to society. In future, scientific drilling for faulting and earthquakes processes, for heat and mass transport, for global cycles and environmental change and for the hidden biosphere shall be considered in the context of societal needs and relevance such as water quality and availability, climate and ecosystem evolution, energy and mineral resources and natural hazards.

The conference served to (i) review ICDP activities and highlight past achievements, (ii) identify new hot topics, (iii) strengthen and expand ties between member countries and partner programs (IODP, ANDRILL), (iv) invite and integrate early career researchers in upcoming ICDP activities, (v) debate incorporation of industry partners into selected ICDP strategic activities for a science-driven mutual benefit and (vi) discuss new outreach measures to media, policy makers and the interested public. The successful cooperation between ICDP and IODP/ECORD was highlighted and shall be further developed in the future.

All talks and discussions were video-streamed and are available at the ICDP website (http://www.icdp-online.org/media/icdp-science-conference-2013/conference-videos/). A white paper serving for the forthcoming years as ICDP science plan is currently in the make, and a special issue of a scientific journal will present key papers discussed during the conference to provide a snapshot of the scientific framework within which ICDP operates.

**Thomas Wiersberg, ICDP**

# Schedules

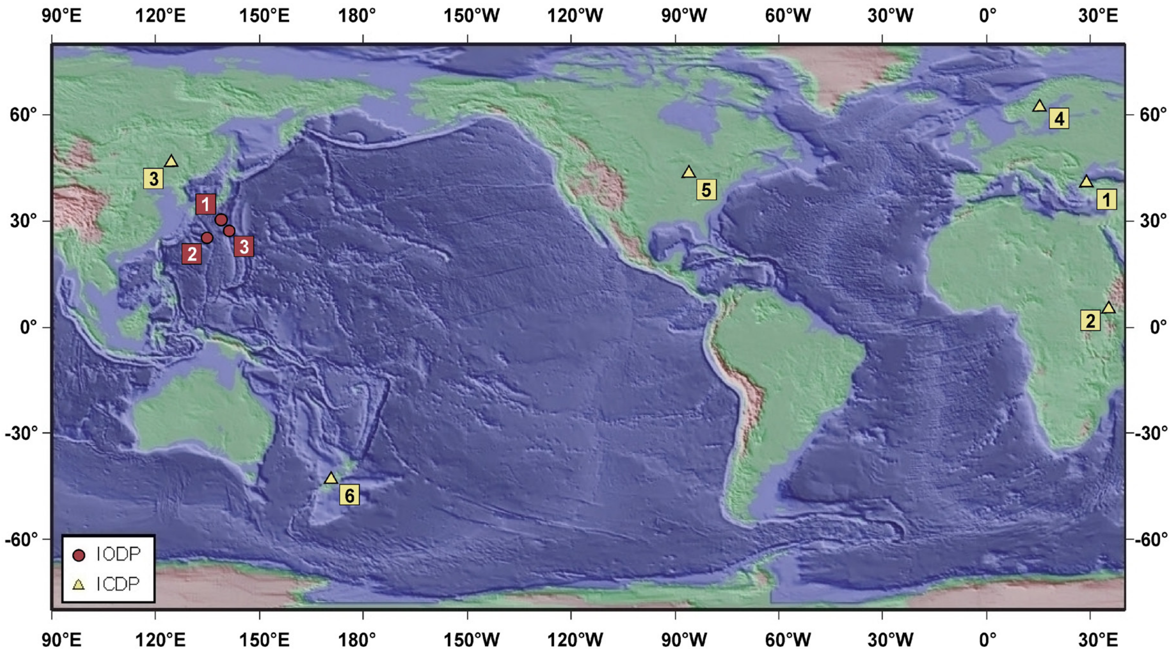
## **IODP** – Expedition Schedule http://www.iodp.org/expeditions/

| USIO Operations | Platform | Dates | Port of Origin |
|---|---|---|---|
| 1 350 Izu Bonin Mariana Reararc | JOIDES Resolution | 30 Mar–30 May 2014 | Okinawa, Japan |
| 2 351 Izu Bonin Mariana Arc Origins | JOIDES Resolution | 30 May–30 Jul 2014 | Yokohama, Japan |
| 3 352 Izu Bonin Mariana Forearc | JOIDES Resolution | 30 Jul–29 Sep 2014 | Yokohama, Japan |

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

| ICDP Project | Drilling Dates | Location |
|---|---|---|
| 1 GONAF | since Sep 2012 | Istanbul, Turkey |
| 2 HSPDP | Jun 2013–Dec 2014 | Kenya, Ethiopia |
| 3 Songliao Basin | Apr 2014–Apr 2015 | Songliao Basin, China |
| 4 COSC | Apr–Sep 2014 | Jämtland, Sweden |
| 5 IDRAS | Sep 2014 | Illinois, USA |
| 6 Alpine Fault | Sep–Nov 2014 | South Island, New Zealand |

## Locations



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