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Scientific Drilling

Reports on Deep Earth Sampling and Monitoring

Dear readers,

With two workshop reports and one progress report, the present volume of Scientific Drilling puts a special focus on planned and running scientific drilling projects in the South American tropics, so far a "terra incognita" for deep scientific drilling.

One workshop report (p. 33) discusses the feasibility and the expectations of deep drilling of the Colônia structure at the southwest margin of the city of São Paulo, a circular structure of 3.6km in diameter and unknown origin. Deep scientific drilling of the structure is required to provide a means of deriving its origin. Moreover, the Colônia Basin has remained a closed basin system ever since its formation, making the sedimentary infill an extended and unique paleoenvironmental record for the Southern Hemisphere tropics.

The evolution of plant biodiversity in the Amazon forests and the biodiversity response to changes in the physical environment, including climate, tectonism, and landscape, were addressed by the Trans-Amazon drilling workshop (p. 41). To archive these goals, long sedimentary records from each of the major sedimentary basins across the heart of the Brazilian Amazon are required.

Sediment cores were already collected from the Xingu River (p. 21) and from floodplain lakes of the Volta Grande, a particularly fluvial landscape of the Xingu River's downstream sector, to improve our knowledge on the origin of the Volta Grande, its fluvial dynamics, and its late Quaternary changes in vegetation, hydrology and biogeochemistry. Scientific drilling will also provide valuable information to forecast future impacts on biodiversity resulting from the operation of the Belo Monte hydropower plant.

Linking bio- and geosciences was an important target of other scientific drilling efforts. The International Ocean Discovery Program (IODP) Expedition 347 (p. 1) cored sediments from different settings of the Baltic Sea covering the last glacial-interglacial cycles. The main aim was to study the geological development of the Baltic Sea in relation to the extreme climate variability of the region with changing ice cover and major shifts in temperature, salinity and biological communities. The European Consortium for Ocean Research Drilling (ECORD) mission-specific platform drilling recovered 1.6km of core from nine sites, four of which were additionally cored for microbiology.

A new drilling campaign at the Surtsey Volcano (p. 51) will use the natural laboratory of the Surtsey tephra above and below sea level to shed light on hydrothermal seawater–rock interactions in rift zone volcanism, the succession of early microbial life, and microbial interactions with basaltic tephra using volcanological, microbial, geochemical, mineralogical, and geoarchaeological approaches.

A more general approach, namely to help advance deep biosphere and paleoclimate research by identifying needed improvements in scientific drilling planning and available technology, sample collection and initial analysis, and long-term storage of subsurface samples and data was topic of a IODP/ICDP/DCO/J-DESC/MagellanPlus workshop (p. 59).

An 82m long core was recovered from the central eastern Fucino Basin (p. 13) in June 2015. The major goals of this drilling were to collect a continuous record back to marine isotope stage 6, to assess the quality of the lacustrine sedimentary succession, to explore the sensitivity of different paleoclimatic proxies, and to document the presence of widespread tephras useful for regional to extra-regional correlation.

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 Engineering Developments, Technical Developments, Workshops, Progress Reports, and news and updates from the community.

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Cover figures:
Insert1: Diversity of the 644 suckermouth armored catfish species (Loricariidae) in the Xingu River, with an emphasis on lithophilous species (Sawakuchi et al., this volume).
Insert2: Drilling of core CO 14-1 performed during the excursion to the Colônia structure (Ledru et al., this volume).

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Scientific Drilling
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Science Reports

IODP expedition 347: Baltic Sea basin paleoenvironment and biosphere

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Abstract. The Integrated Ocean Drilling Program (IODP) expedition 347 cored sediments from different settings of the Baltic Sea covering the last glacial–interglacial cycle. The main aim was to study the geological development of the Baltic Sea in relation to the extreme climate variability of the region with changing ice cover and major shifts in temperature, salinity, and biological communities. Using the *Greatship Manisha* as a European Consortium for Ocean Research Drilling (ECORD) mission-specific platform, we recovered 1.6 km of core from nine sites of which four were additionally cored for microbiology. The sites covered the gateway to the North Sea and Atlantic Ocean, several sub-basins in the southern Baltic Sea, a deep basin in the central Baltic Sea, and a river estuary in the north.

The waxing and waning of the Scandinavian ice sheet has profoundly affected the Baltic Sea sediments. During the Weichselian, progressing glaciers reshaped the submarine landscape and displaced sedimentary deposits from earlier Quaternary time. As the glaciers retreated they left a complex pattern of till, sand, and lacustrine clay, which in the basins has since been covered by a thick deposit of Holocene, organic-rich clay. Due to the stratified water column of the brackish Baltic Sea and the recurrent and widespread anoxia, the deeper basins harbor laminated sediments that provide a unique opportunity for high-resolution chronological studies.

The Baltic Sea is a eutrophic intra-continental sea that is strongly impacted by terrestrial runoff and nutrient fluxes. The Holocene deposits are recorded today to be up to 50 m deep and geochemically affected by diagenetic alterations driven by organic matter degradation. Many of the cored sequences were highly supersaturated with respect to methane, which caused strong degassing upon core recovery. The depth distributions of conservative sea water ions still reflected the transition at the end of the last glaciation from fresh-water clays to Holocene brackish mud. High-resolution sampling and analyses of interstitial water chemistry revealed the intensive mineralization and zonation of the predominant biogeochemical processes. Quantification of microbial cells in the sediments yielded some of the highest cell densities yet recorded by scientific drilling.

1 Introduction

The Baltic Sea basin (BSB) is one of the world's largest intra-continental basins, occupying 373 000 km^2 and with a drainage area 4 times this size (Fig. 1). Its mean depth is ∼ 54 m, although a few relatively deep basins exist (e.g., the eastern Gotland Basin, 248 m, and the Landsort Deep, 459 m). The BSB has served as depositional sink throughout at least the last during the last glacial cycle and its sediments comprise a unique high-resolution archive of the paleoenvironmental history of the large drainage area, the basin itself, and the neighboring gateways to the North Sea. The location of the BSB in the heartland of the recurring Scandinavian ice sheet (SIS) has resulted in a complex developmental history, characteristic of many glaciated regions of the Northern Hemisphere: repeated glaciations of different magnitudes, sensitive responses to sea-level and gateway thresh-

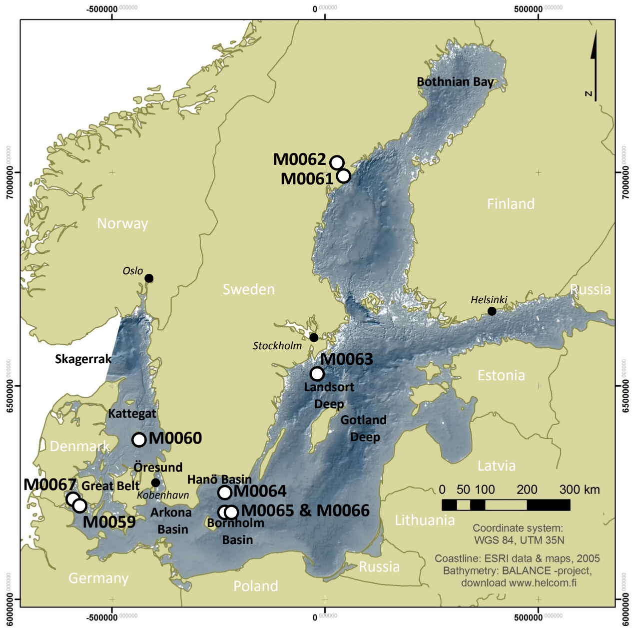

Figure 1. Bathymetric map of the Baltic Sea with the nine coring sites, M0059 to M0067. Source: IODP Leg 347 expedition Report.

old changes, large shifts in sedimentation patterns, and high sedimentation rates.

The geographical position of the BSB makes it a unique link between the Eurasian and the northwest European terrestrial records and as such also serves as a link to the North Atlantic marine records and the Greenland ice cores.

The high sedimentation rates (100–500 cm/1000 years) of the BSB provide an excellent opportunity to reconstruct in some parts climate variability of global importance controlled by, for example, changes in meridional overturning circulation (MOC), the North Atlantic Oscillation (NAO), and the Arctic oscillation (AO). These paleoenvironmental reconstructions offers a unique resolution from a marine-brackish setting as some of the sediments can even be resolved on inter-annual timescales. This makes the BSB highly suitable for sediment coring from the last glacial cycle and a unique location to achieve scientific objectives of high-resolution paleoceanography and paleoclimate studies, as comparable sequences cannot be retrieved anywhere in the surrounding onshore regions.

2 Glacial–interglacial history of the Baltic Sea basin

The BSB has undergone many glaciations during the Quaternary. During the last interglacial (the Eemian, marine isotope stage (MIS) 5e), the BSB was a larger and more saline sea than the present Baltic Sea (Funder et al., 2002). Only fragments of the Baltic glacial history are known. However, we do know that a Baltic glacial event occurred during MIS 4 as recorded in sediments from northwest Finland at ∼ 64° N

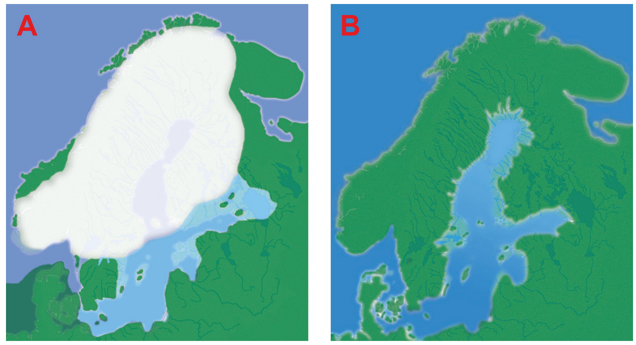

Figure 2. **(a)** Estimated extension of the Scandinavian ice sheet at 11.7 ky BP just prior to the final drainage of the Baltic Ice Lake. Dark blue: Atlantic Ocean, light blue: Baltic Ice Lake. **(b)** Extension of the Littorina Sea during the time of maximum salinity in the Baltic basin at ca. 6 ky BP. Source: Andrén et al. (2011).

(Salonen et al., 2007). The first Baltic ice lobe that advanced into Denmark is dated to ∼ 55–50 ky BP (thousand years before present; Houmark-Nielsen, 2007). From detailed correlations and dating of southwestern Baltic glacial stratigraphies (Houmark-Nielsen and Kjær, 2003), it is proposed that the southwestern Baltic experienced two major ice advances during MIS 3, at ∼ 50 and 30 ky BP. However, the latter is highly debated (e.g., Kjellström et al., 2010). This enigmatic period between ∼ 50 and 25 ky BP, with its partly incompatible records, was followed by a complex glaciation in the southern BSB (Houmark-Nielsen and Kjær, 2003) leading up to the Last Glacial Maximum.

Deglaciation of the southern BSB between 22 and 16 ky BP was complex, with major deglacial phases interrupted by some intriguing SIS still stands and re-advances (Houmark-Nielsen and Kjær, 2003; Larsen et al., 2009), possibly as surges.

Earlier studies have suggested that the Younger Dryas cold event (12.9 to 11.6 ky BP) was caused by freshwater runoff from the Laurentide (American) ice sheet slowing the Atlantic MOC (Marshall and Clark, 1999). However, state-of-the-art climate models require a continuous freshwater forcing to produce millennia-long cold events (Liu et al., 2009) and there are indications of substantial freshwater forcing from the BSB predating the final drainage from the Baltic Ice Lake (e.g., Björck, 1995; Bennicke and Jensen, 2013).

During the final drainage of the Baltic Ice Lake at ∼ 11.7 ky BP (Fig. 2a), almost 8000 km^3 of freshwater was released rapidly into the North Atlantic (Jakobsson et al., 2007).

The next Baltic Sea stage, the Yoldia Sea, coincided with the onset of the Holocene epoch (Walker et al., 2009) and the associated rapid warming. In fact, the thicknesses of glacial varves in the northwestern Baltic proper and δ^{18}O values in ice cores from the Greenland Ice Core Project (GRIP) display a noticeably similar pattern over a 150-year-long transition period from Younger Dryas to pre-Boreal (Andrén et al., 1999, 2002). These records show a distinct increase in sedimentation rate as the ice sheet began to melt and rapidly retreat. The following few hundred years were characterized by rapid deglaciation of the SIS. Relative sea-level lowering of the Yoldia Sea played an important role and were the result of a combination of rapid regression in the recently deglaciated regions and normal regression rates in southern Sweden (1.5–2 m/100 years).

As the outlets to the west became shallower, subsequent damming forced the water level inside the Baltic Basin to rise and the next stage began, the Ancylus Lake. The sediments of this large freshwater lake generally contain little organic material, which may be explained as a result of the large meltwater inflow to the Baltic from the final deglaciation of the SIS and also a result of erosion of the young soils from the recently deglaciated drainage area. This created a lake environment with low nutrient input and hence low productivity. The freshwater environment did not enable the formation of a halocline but led to a well-mixed, oxygenated waterbody. The relatively common sulfide-banded sediments of this stage can probably be explained by later H_2S diffusion from overlying, organic-rich Holocene sediments (Sohlenius et al., 2001).

The global melting of the large ice sheets over a couple of millennia caused a 30 m rise in absolute sea level (Lambeck and Chappell, 2001). A consequence of this was the flooding of the Öresund Strait, believed to be the main gateway for the onset of the marine Littorina Sea stage. The outlets/inlets through Öresund and Great Belt widened and became deeper, resulting in greater water flow and gradually increasing salinity.

The onset of the Littorina Sea stage can often be recognized as a marked lithologic change in Baltic Sea sediment cores. The onset is represented by a distinct increase in organic content and an increasing abundance of brackish-marine diatoms (e.g., Sohlenius et al., 2001).

Periods of deep-water hypoxia in the open Baltic Basin are evident in the sediment record as extended sequences of laminated sediment. The Littorina Sea (Fig. 2b) experienced a sustained period of elevated salinity and resulting hypoxia between 8 and 4 ky BP (Zillén et al., 2008). After $\sim$4 ky BP, the salinity decreased gradually and oxygen concentrations increased in the bottom waters.

The human population growth and large-scale changes in land use that occurred in the Baltic Sea watershed during the Medieval period between AD 750 and 1300 has been suggested as a triggering mechanism behind the expansion of hypoxia that again occurred at this time (Zillén et al., 2008). Alternative hypotheses suggest that the development of hypoxia in the open Baltic Sea over the past 1000 years has mainly been driven by the climate system (e.g., Kabel et al., 2012).

3 Scientific objectives

The objectives of expedition 347 are categorized below.

Geology and climate development objectives include the following:

- to increase our understanding of the climate system and the sea-level dynamics of the last interglacial, including the climatic oscillations at the transition between MIS 6 and MIS 5e, and in the initial, climatically oscillating part of the last glacial (MIS 5d–5a);
- to analyze environmental conditions during the warmest interval of MIS 5e to elucidate possible future scenarios during warmer climate and higher sea-level stands;
- to evaluate how strongly the SIS responded, in time and space, to North Atlantic climate forcing during the last glacial, and to what extent the dynamic alterations of the SIS had an impact on the North Atlantic climate system;
- to understand the feedbacks between the waterbody of the BSB, the SIS, and the North Atlantic circulation;
- to determine to what degree the glacier oscillations of the SIS margin were synchronous on both sides of the main ice divide, centered along the Scandinavian mountain chain, and whether the ice advances into the southern BSB can be recognized as large-scale surges;
- to describe how the highly oscillating climate pattern of MIS 3 is recorded at the northeast margin of the North Atlantic in long and continuous sediment sequences in the BSB;
- to analyze if there are solar forcing signals in the melting record of the shrinking ice sheet or in the precipitation-related fluvial system;
- to reconstruct river discharge (and thereby also precipitation) with annual resolution, several millennia back in time;
- to determine how the in- and outflows to the Baltic Sea have varied over time, and how this is related to changes in large-scale atmospheric circulation and sea level (threshold depths);
- to analyze how the general precipitation pattern, which is linked to the dominating AO–NAO system over the northern circum-Atlantic and circum-Arctic region, change during the Holocene.

Microbiology and geochemistry objectives include the following:

- to understand how microbial cell numbers are controlled in relation to depth, age, lithology, and other environmental parameters in relatively young and organic-rich marine sediments;

– to determine the diversity and activity of subsurface microbial communities through metagenomic, metatranscriptomic, and single-cell genomic analyses;

– to determine whether the predominant microorganisms are selected by environmental conditions prevailing in the subsurface today;

– to determine whether the sub-seafloor microbial communities reflect past environmental conditions, e.g., seawater or freshwater, cold or temperate climate, oxic or anoxic bottom water;

– to analyze whether viruses and unicellular eukaryotes play a role in the subsurface sediments;

– to model and interpret past climate and paleoenvironment of the Baltic Sea basin from geochemical proxies;

– to analyze how the major glacial–interglacial shifts in the Baltic Sea affect sediment geochemistry today;

– to understand how nutrient loading, organic productivity and hypoxia have varied in the Baltic Sea throughout the Holocene and what are the forcing factors.

4 Coring operations and strategy

The drilling platform chosen for expedition 347 was the *Greatship Manisha*, an IMO (International Maritime Organization) Class II dynamically positioned vessel with geotechnical coring capability (Fig. 3a). The mobilization took place in Falmouth prior to transit to Kiel, Germany, where the ESO (ECORD (European Consortium for Ocean Research Drilling) Science Operator) expedition project managers and offshore science party participants boarded the vessel following a pre-cruise scientific meeting in Copenhagen. Operations were conducted between 12 September and 1 November, with demobilization of the vessel occurring back in Falmouth on 5 and 6 November. In total, 37.1 days of expedition 347 were spent operational on station, 8.5 days in transit between sites, 1.3 days in port, 1.3 days on standby at station because of weather, and 1.8 days on equipment-related downtime.

The vessel was equipped with a large moon pool and Geoquip GMTR 120 heave-compensated derrick, with a 120 metric ton capacity top drive. Pipe handling was carried out using a proprietary semiautomated handling system utilizing a pipe handling crane with grab, a remotely operated iron roughneck, and a proprietary catwalk system. A 4 m stroke passive heave compensation (semiactive under development) was achieved using nitrogen gas as a compensation buffer with Olmsted valve slingshot protection. The rig was used in association with a 12 metric ton seabed template, fitted with clamps and seabed transponder, to provide the reaction force for in-hole tools. Wireline operation of the core barrel was conducted through the top drive.

Five methods of wireline coring were employed in addition to open-hole drilling using a non-coring assembly. The primary coring tool was a piston corer system (PCS), operated by advancing the core barrel into the formation through hydraulic pushing. However, where formation lithologies were either unconsolidated, noncohesive, friable or very hard, an extended coring system (ECS), non-rotating core barrel system (NRCB), push coring assembly (PCA), or hammer sampler (HS) were employed. The HS was the most rudimentary system used during this expedition, consisting of a built-in hammer, which was raised and lowered onto an anvil over a few meters distance. This tool was used to obtain a spot sample when open-holing through coarser-grained deposits, or when conventional coring methods had been unable to acquire a sample. The non-coring assemble (NCA) used a Tricone Rock Roller drill bit to plug the hole in the main core bit to advance without recovery.

The core collected was 62 mm in diameter. The maximum core run length was 3.3 m. However, the length of a core run was chosen to maximize core recovery and quality while maintaining hole stability, even at the expense of overall penetration speed. When attempting to capture a lithologic interface, as defined from seismic profiles, the run lengths were often shortened by raising the corer above the bottom of the borehole by a known height prior to pressuring the drill string. In some instances, the hole was advanced by open holing – drilling ahead without recovering sediments. This was done in difficult lithologies that could not be recovered conventionally to enable recovery of other lithologies beneath these intervals or when recovery (composite or from an individual hole) of an interval had already reached > 90 %, and the scientific rationale was to try and get deeper within the time constraints. The advance varied from a small offset of 0.5 m to ensure maximum core overlap between holes in some locations to a more regular spacing of 3 m through the till lithologies to monitor when or whether the lithology was changing.

At the Ångermanälven River estuary site (M0061), there were initial restrictions on coring the upper 50 cm of sediment due to potential heavy metal contamination from industry. This was relaxed on assessment on-site. At Hanö Bay, Bornholm basin, and Anholt loch sites (M0064, M0065, and M0060, respectively), downpipe camera or ROV (remotely operated vehicle) surveys were conducted prior to commencing coring, due to the potential for dumped WWII munitions on the seabed. In addition, restrictions were placed on coring the upper 2m of sediment at Bornholm Basin (M0065) due to the risk of dumped chemical munitions.

Offshore, the cores from paleo-oceanographic designated holes were carefully curated by ESO staff before ephemeral physical (multi-sensor core logger, MSCL) and geochemical properties were measured and preliminary core catcher samples taken. Initial lithological and micropaleontological descriptions were conducted by visual inspection through the liner and by using core catcher materials. No further sam-

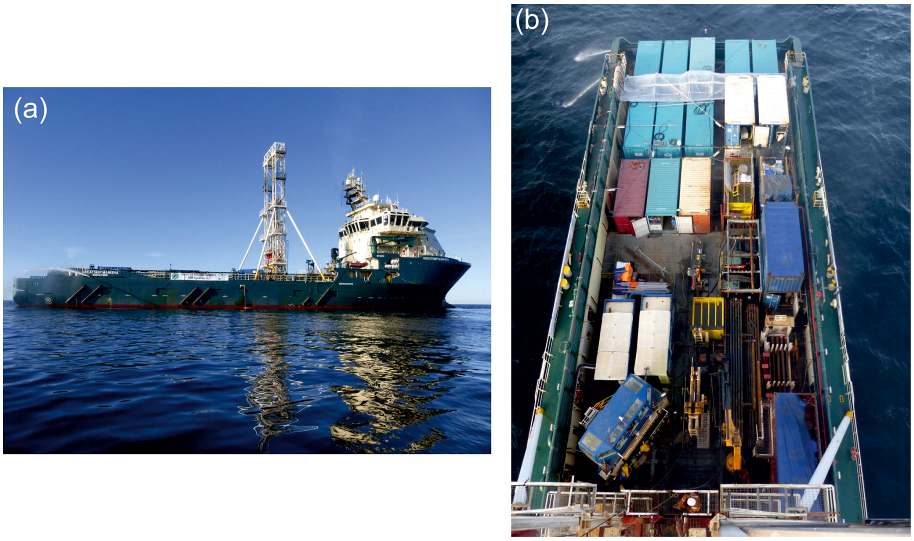

Figure 3. (a) The geotechnical vessel, *Greatship Manisha* (of Singapore) equipped with a drilling derrick. **(b)** View from the derrick over the drill deck at mid-ship and the "science garden" to the aft. Image copyright ECORD/IODP.

pling, core splitting, or analysis work was undertaken offshore.

On microbiological designated holes, samples were taken on the drill floor from the cut ends of core sections to capture ephemeral properties, including methane gas and contamination tracer quantities. The cores were then curated and run through a fast-track MSCL prior to extensive sampling in the designated laboratory containers (Fig. 3b) for microbiological research and for interstitial water analyses. In total > 5800 samples were taken offshore.

All cores, core catchers, headspace gas samples, interstitial water splits, and digital data were transferred to the Integrated Ocean Drilling Program (IODP) core repository in Bremen, Germany (BCR), at the end of the offshore phase. Prior to the start of the Onshore Science Party (OSP), additional thermal conductivity measurements and natural gamma radiation measurements were conducted on whole core sections. The complete science party, as well as ESO and BCR personnel and student helpers, met at the BCR from 22 January to 21 February to split, analyze, and sample the cores according to standard IODP procedures, and for post-cruise scientific research.

5 Preliminary expedition results

In the following we present selected preliminary results from leg 347 on lithology, biostratigraphy, dating, geochemistry, and microbiology. By these chosen examples we briefly summarize how the expedition met some of the objectives outlined above.

5.1 Little Belt (sites M0059 and M0067)

The lithology consists of diamicton interlayered with sand and silt in the lower part of the core (Fig. 4a). These layers give OSL (optically stimulated luminescence) ages between ca. 362 ky BP at 146 m b.s.f. (meters below seafloor) and ca. 103 ky BP at 108 m b.s.f. This means that the sediments between these two levels have recorded MIS 5. The recovered stratigraphy is, however, fragmented but represents nonetheless a unique archive of a Pleistocene time window never recovered before in the Baltic Sea. On top of this unit, at ~ 90–83 m b.s.f., is a 11 m thick sandy deposit with silt and clay laminas. The OSL date from these sediments is ca. 44 ky BP.

From 82 to 52 m b.s.f., glacial ice lake sediment is deposited as varved glacial clay displaying thick varves in the lower part and thinner varves deposited distal to the retreating ice margin in the upper part. This unit is erosionally truncated and marked by a 2 cm thick sandy-silty layer at 52 m b.s.f. displaying an upwards coarsening, which indicates deposition during a rapid regression. The contact upwards to the overlaying gyttja clay is sharp and possibly also erosional.

At site M0059 we recovered 52 m of Holocene sediment with a correspondingly high-mean sedimentation rate of 5–7 mm year^{-1} based on four radiocarbon dates received so far. The diatom flora in this unit of organic-rich clay has recorded a sharp transition from freshwater to fully marine conditions at ca. 48 m b.s.f., indicating a rapid marine transgression (Fig. 4c). It should be noted, however, that final conclusions cannot be drawn until the sequence has become more thoroughly analyzed.

From site M0067 we only recovered ca. 4.4 m of Holocene mud on top of medium to coarse sand interlayered with silt

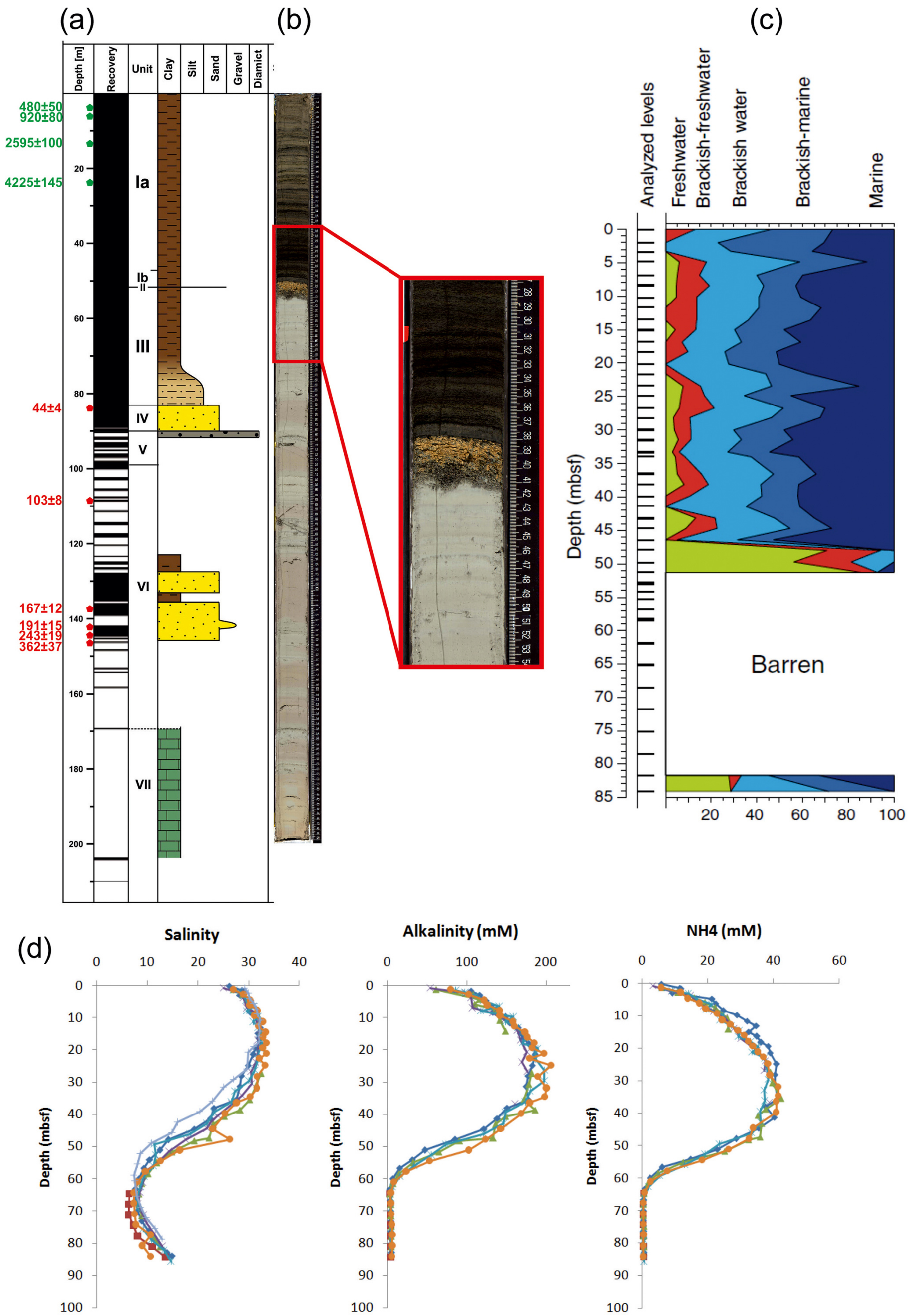

Figure 4. Little Belt, site M0059. **(a)**Lithostratography with ages: green is ages derived from ^{14}C dating given in cal yr BP and red is ages derived from OSL dating given in ky BP. **(b)** Section 347-M0059A-16H-2 from 52 m b.s.f. shows the hiatus sand horizon of unit II at the transition from the varved clay sequence of Unit III into the laminated black organic-rich clay of subunit Ib. Inset: close-up of the coarse-grained, poorly sorted sand hiatus marking a low stand. **(c)** Relative distributions of diatom taxa according to their preferred habitat salinity. **(d)** Examples of interstitial water chemistry: diffraction-based salinity, alkalinity, and ammonium. Different symbols show data from different holes.

and clay, interpreted having a glaciofluvial ice-proximal origin. There is obviously a large hiatus at this site.

The depth distributions of conservative seawater ions in the interstitial water showed a distinct drop from seawater salinity in the Holocene sequence to a minimum in salinity in the underlying glacial ice lake clay (Fig. 4d). Interestingly, chloride-based salinity calculations did not show a broad maximum at 10–30 m b.s.f. as did the diffraction-based salinity, which is affected by all ions in the interstitial water. The difference is due to very high DIC (dissolved inorganic carbon) and ammonium concentrations that add to the diffraction-based salinity. These data reflect extremely high rates of organic matter mineralization in the 50 m deep, organic-rich Holocene clay. Thus, alkalinity values were up to 200 mM, which is probably a new IODP record, while ammonium reached 40 mM.

5.2 Kattegat (site M0060)

From site M0060 we cored a > 200 m deep, almost continuous record that consists of an 84 m diamict unit, in the lowermost part of the core. On top of this unit alternating sandy and silty sequences are recorded with a unit between 79 and 6 m b.s.f. that consists of varved glacial clay indicating deposition in a glacial lake or marginal marine environment. It is possible that this varved unit records freshwater outflow from the Baltic basin, and it is therefore anticipated that it will give a yearly resolution.

A gradually decreasing salinity was recorded down to ca. 125 m b.s.f. at this site below, which the salinity increased distinctly again. Together with the foraminifera and ostracode records this indicates a marine provenance of the sediments below this level. Throughout the hole, cores also displayed abundant snail and bivalve shells that will be useful for both dating and environmental reconstruction.

The sediment had surprisingly low mineralization rates with mainly sulfate reduction and iron reduction as the dominant terminal processes of organic matter oxidation. Methane appeared only at depths between 100 and 170 m b.s.f. This methane is possibly not produced on site in the low-organic diamict unit but may have been transported over a distance via the over-pressured sandy aquifer.

5.3 Ångermanälven River estuary (sites M0061 and M0062)

These two northernmost sites were selected as it was known that annual varves have been deposited over several thousand years and are still being formed at the mouth of the river. The many hundred years of varved sequences collected at these sites will be correlated with and included in the so-called Swedish Time Scale, a continuous varve chronology covering the time span from ca. 13 300 clay-varve years BP to the present.

At both sites ca. 20 m of sediments were recovered, which displayed varves that were 4–10 cm thick in the lower part and only a few millimeters thick in the upper part. At site M0061 organic-rich mud in the uppermost 8 m displayed a brackish influence that was evident from both the foraminifer and ostracode fauna and from the diatom flora. It is noteworthy that this is the first report of foraminifers and ostracodes in sediments of Holocene age this far north in the Baltic Sea.

5.4 Landsort Deep (site M0063)

In the Landsort Deep, which is the deepest basin in the Baltic Sea, we cored to a depth of 95 m b.s.f. in a water depth of 437 m. At the deepest part between 95.8 and 93.4 m b.s.f. the sediment consists of a clast-poor sandy diamicton overlaid by a 53 m thick unit of varved glacial clay. This uniquely long varve sequence may enable a correlation to the Greenland ice core record (cf. Andrén et al., 1999, 2002). The varves can possibly comprise as much as 2,000 years in one continuous sedimentary record and may have recorded, with annual resolution, the entire Younger Dryas as well as its onset and termination (Fig. 5). In the upper part of this varved unit at 41.5 m b.s.f. a weak brackish influence is recorded in both the ostracode fauna and in the diatom flora, which is interpreted as representing the short brackish phase of the Yoldia Sea stage.

The overlaying grey homogenous clay converts gradually into a laminated organic-rich mud and the first substantial inflows of marine water are registered at 28 m b.s.f., as observed from a decrease in freshwater and increase in brackish water diatom species and an increased abundance of foraminifers. This first inflow is also registered as an increasing salinity in the chemistry of the pore-water and probably represents the transition from the lacustrine Ancylus Lake stage to the brackish-marine Littorina Sea stage.

The uppermost 28 m of the cored sediments consists of a laminated organic-rich mud, sometimes referred to as clay gyttja in Baltic Sea geological literature. This type of sediment indicates that the deepest part of the Landsort Deep has been anoxic/hypoxic during the last ca. 7000 years. So far we have only one ^{14}C date from this unit at 24.6 m b.s.f. yielding an age of 5850 $\pm$ 120 cal yr BP.

5.5 Hanö Bay (site M0064)

Four holes were drilled at this site of which three recovered an almost 30 m long unit of clast-rich, stratified, muddy diamicton on top of a unit of sandy clayey silt with thin intervals of diamicton. Varved glacial clay deposited on top of this diamicton consisted of two different sub-units, a lower dark-brownish-grey clay and an upper dark-greyish-brown clay separated by a 2–3 cm thick organic-rich (LOI, loss on ignition; ca. 8 %) brown silty clay (84–87 cm in section (b), Fig. 6). This unit has been ^{14}C dated in two cores and the mean age of the unit is 45 700 $\pm$ 1500 cal yr BP, which means that this lower varved clay sequence was deposited during a deglaciation much older than the latest one.

5.6 Bornholm Basin (sites M0065 and M0066)

The lithologies from these two sites are quite similar. The lowermost 40 m of the stratigraphy consists of the same two different types of varved glacial clays as at site M0064 although more expanded. Also at site M0065 the two clay units are separated by a homogenous dark-grey layer, here with a

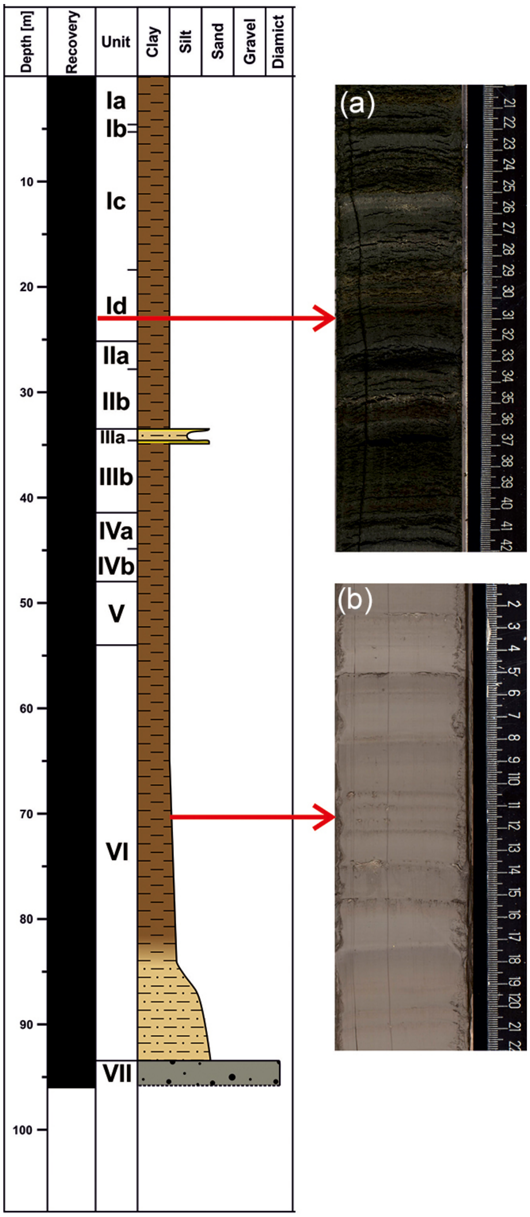

Figure 5. Landsort Deep, site M0063. Lithostratigraphy with insets **(a)** laminated Littorina Sea mud (section 347-M0063C-12H-2) and **(b)** varved Baltic Ice Lake glacial clay (section 347-M0063C-34H-2).

thickness of 60 cm, which probably corresponds to the dated layer at site M0064.

A shift from freshwater to brackish conditions is recorded in the diatom flora at 10 m b.s.f. and most probably represents the Ancylus Lake–Littorina Sea transition (Fig. 7). The lowermost part of this unit is laminated whereas the upper 9 m is homogenous and contains abundant mollusk shell fragments indicating well-oxygenated bottom water conditions.

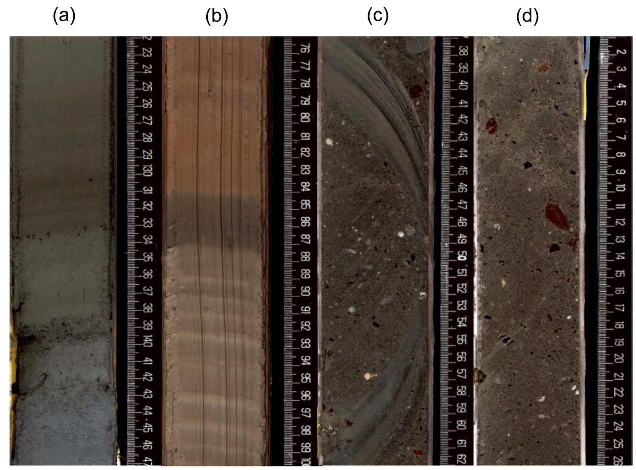

Figure 6. Hanö Bay, site M0064. Examples of varved glacial clay (**a** and **b**) and diamicton **(c, d)**. The greyish brown unit between 84 and 87 cm separating the two different types of varved glacial clays in section b have an age of 45 700 ± 1500 cal yr BP.

5.7 Microbiology

Cell enumeration was done on board the *Greatship Manisha* by two different approaches. One was the well-established epifluorescence counting of samples in which cells had been DNA stained with the fluorescent dye, acridine orange. The other was flow cytometry whereby cells were first extracted quantitatively from the sediment and DNA stained with the fluorescent dye, SYBR (Synergy Brands Inc.) green. In the flow cytometer, which was provided by the Kochi Core Repository, these cells were counted automatically at a high rate, which increased the capacity for onboard cell counts. Importantly, comparison of the two techniques provided very similar cell numbers in most sediments studied. In some sediment intervals, however, flow cytometry provided lower numbers than fluorescence microscopy. This could be explained by incomplete detachment of cells from exopolysaccharide particles, which prevented counting in the flow cytometer but still enabled microscopic counting.

Microbial cell abundances were extremely high at all sites studied, even exceeding 10^{10} cells cm^{-3} in the Bornholm Basin, a new record for the IODP. Cell numbers also remained surprisingly high at depth. This is in accordance with the high organic carbon content in the Holocene deposits and the high sedimentation rates. As an example from site M0059 in Little Belt, the cell density was 10^9 cells cm^{-3} at the sediment surface and dropped only by 1 order of magnitude at the bottom of the Holocene at 50 m b.s.f. where the sediment had an estimated age of > 9000 years (Fig. 8a). Cell numbers for site M0063 in the Landsort Deep (Fig. 8b) provided another example of a good correspondence between the two enumeration techniques in the lower part of the hole but showed an increasing divergence towards the sediment surface due to the described incomplete dispersion of cells.

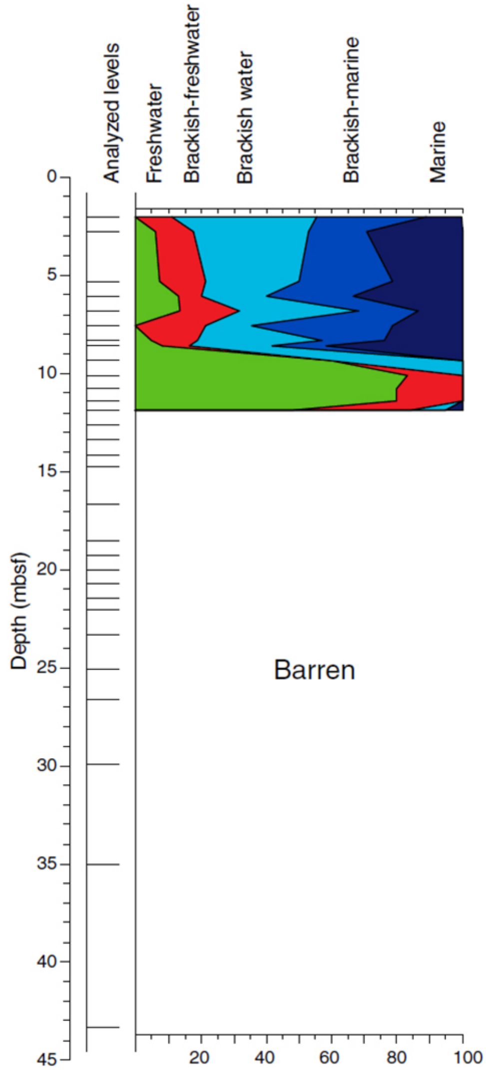

Figure 7. Bornholm Basin, site M0065. Relative distribution of diatom taxa according to their preferred habitat salinity.

Since it was not possible on this mission-specific platform to perform any microbiological analyses other than cell counts, samples needed to be fixed and/or frozen to be preserved for later studies in land-based laboratories. Freezing may damage cell structures and can be a problem for studies that depend on intact cells, such as fluorescence in situ hybridization (FISH or CARD-FISH). However, a new CAS (Cells Alive System) freezer technique, provided by the Kochi Core Repository, was available on board. By this technique samples are cooled during exposure to a high-frequency alternating electromagnetic field. When the temperature reaches −10 °C the electromagnetic field is switched off and freezing happens almost instantaneously, which prevents the formation of ice crystals of a size that damages cell structures.

When drilling the holes for microbiology at four sites, contamination tests were carried out (Smith et al., 2000; Lever et al., 2006). A perfluorocarbon (PFC) tracer was pumped continuously into the drilling fluid and samples were taken from three radial positions in each core immediately upon recovery and cutting on the drill deck. As a new procedure for IODP, samples were also taken routinely from fluid remaining in the core liner. Since this represents the fluid to which the cores were exposed when taken in situ, these fluid samples optimally represent the relevant contamination tracer concentration. The results showed that the concentration of the tracer that arrived at the bottom of the drill hole was mostly much lower than the expected target concentration. The conclusion is that this sampling procedure of liner fluid should be implemented on future IODP expeditions. Also the land-based analytical procedure for PFC was improved relative to IODP standard by heating samples while rotating before headspace sampling and GC-ECD (gas chromatography with electron capture detector) analysis (M. A. Lever, unpublished). Furthermore, this procedure is recommended for future deep biosphere expeditions when analyzing a PFC tracer.

During expedition 347, a large number of samples were taken for many different land-based research groups and for many different types of analysis. In fact, the requested sampling frequency was so high in the upper sediment intervals that most of the core was subsampled and it was occasionally difficult to accommodate all the requests. In order to minimize the impact of high levels of sampling, graphical sampling schemes were developed in advance for each core. For the sampling of whole round cores, a small computer program was developed to facilitate the sampling plan (Marshall, 2014). It was also of great advantage on this expedition that samples for land-based studies that relied on live microorganisms could be off-loaded from the *Greatship Manisha* to a small boat and thereby arrived in the receiving laboratories in Denmark, Germany, and the UK within a few days to a week after coring of each microbiology hole.

6 Conclusions and future work

The OSL ages from site M0059 indicate that we reached at least some 350 ky back in time. Without having all dates at hand, we assume that at site M0060 we recovered sediments dating back to the previous interglacial. This means that the lower part of the holes from these two sites may cover the end of MIS 6, MIS 5, and MIS 4, although with partly fragmented stratigraphies.

Sediments of MIS 3 age have been recovered and dated at site M0059 and site M0064 and are most probably also present in the sediments from site M0065 and perhaps also M0066. The recovered sediments, of pro-glacial sandur at site M0059 and organic-bearing clay at site M0064 and M0065, indicate an ice-free event in the middle of the We-

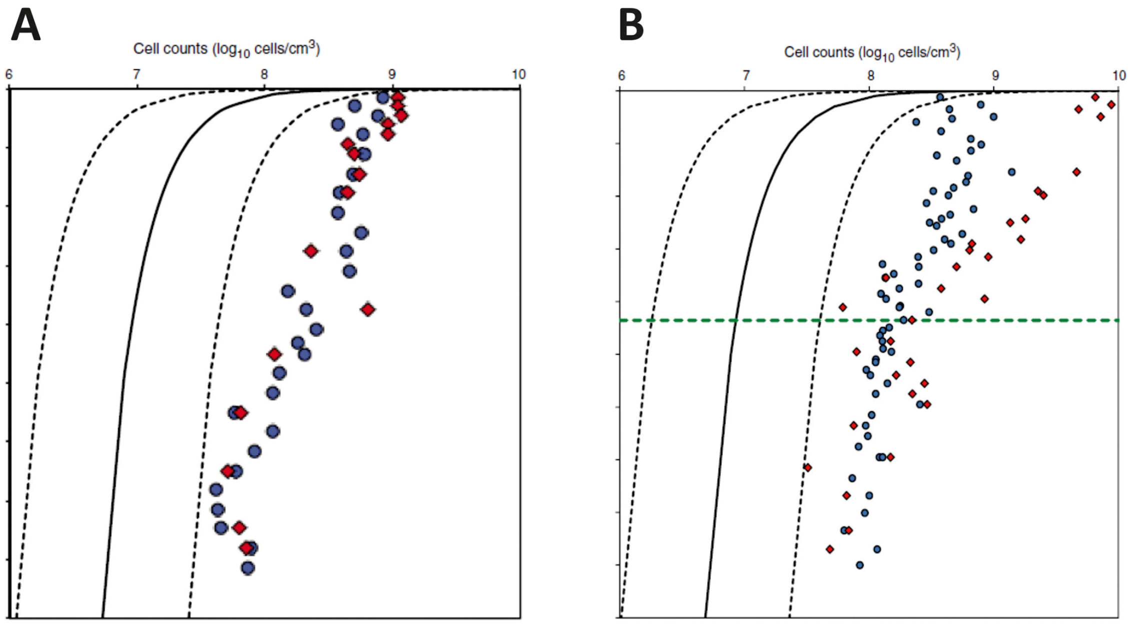

Figure 8. Cell numbers from **(a)** Little Belt, site M0059, and **(b)** the Landsort Deep, site M0063. Red diamonds: cell counts by fluorescence microscopy (AODC, acridine orange direct counts); blue circles: cell counts by flow cytometry. The solid black line is a global regression line of prokaryote cell numbers with depth, while the dashed lines are upper and lower 95 % prediction limits for the regression line (Roussel et al., 2008).

ichselian glacial with an age of 44 ± 4 ky BP. Ongoing analyses of sediments from these sites may shed new light on the history of the BSB and the behavior of the SIS during the enigmatic MIS 3.

Varved glacial clays deposited from the retreating SIS have been recovered at all drilled sites, which makes environmental reconstructions possible with annual resolution. Especially notable are the 52 m long varved sequences from site M0063, possibly containing as much as 2000 varves and probably covering the entire Younger Dryas. This unique varved sequence will give us new insights into how the SIS responded to climate fluctuations, including the slow cooling at the beginning and the rapid warming at the end of the stadial. It will also give new information on the position of the ice margin and thereby improve the correlation between ice margin positions in eastern Sweden and southwestern Finland during the Younger Dryas.

It should be noted that glacial varves have traditionally been assigned to the latest deglaciation but the two units of varved glacial clay separated by an organic-bearing clay with an age of 45 700 ± 1500 cal yr BP indicates a different scenario at site M0064. It is obvious that only the upper varved sequence was deposited during the latest deglaciation whereas the lower sequence represents an earlier deglaciation.

Sediments of Holocene age have been recovered at most drilled sites but at sites M0059 and M0063 the thickness of these sediments is spectacular, ca. 52 m at site M0059 and ca. 45 m at site M0063. The extremely high sedimentation rates at these two sites presented the possibility to reconstruct the environmental response to climate warming leading up to the Holocene thermal maximum, occurring some 8000 to 5000 years ago, with a resolution never reached before in the Baltic Sea area. It will, for example, be possible to detect small variations in, e.g., salinity, nutrient status, temperature, ice cover, and periods of hypoxia/anoxia, possibly with an annual resolution.

Mission-specific platforms routinely work in shallow waters, and so protocols are already in place to maximize the quality and amount of core recovered when working in these environments, building on the knowledge gained from four previous expeditions. However, the scope of the offshore microbiological program was something not undertaken before on an MSP (mission-specific platforms). Thanks to the early and extensive input and support from the microbiological community, we were able to achieve a successful sampling campaign. However, a detailed post-cruise review has shown areas in which additional protocols need to be established in order to improve results in this discipline, e.g., the addition of the contamination tracer to the drilling fluid at higher concentrations.

During expedition 347, four sites were selected for detailed studies of geochemistry and microbiology. Nearly 6000 samples were taken offshore for interstitial water analyses and microbiological studies. The many chemical analyses done on board the *Greatship Manisha* and during the onshore phase have generated data of outstanding quality and detail. The results provide novel insights into the geochemical con-sequences of glacial to interglacial and fresh-water to marine transitions combined with shifts from low-organic late-glacial clay to high organic Holocene clay with extremely high sedimentation rates. These data will be supplemented by a large diversity of inorganic, organic, and isotope geochemical analyses in laboratories around the world.

Detailed contamination tracer measurements were made during the expedition with improved methods relative to previous IODP standards. Off-loading of microbiology samples shortly after drilling enabled cultivation experiments and studies of microbial activity to be done in land-based laboratories and thereby overcome the limited laboratory facilities on the drillship. A comparison of microbial cell counting techniques showed that flow cytometry can provide data of equally good quality as microscopic counts and thereby may enhance the capacity for cell quantification on future drilling expeditions. A new CAS technology enables the freezing of microbiology samples for sensitive post-cruise microbiology studies that require intact DNA/RNA and cell membranes. A large number of samples are currently being analyzed in many different laboratories and will provide metagenomic, metatranscriptomic, and meta-metabolomic data as well as specific data on microbial process rates, cultivation-based microbial diversity, and other information for archaea, bacteria, and eukaryotic microorganisms as well as viruses.

Based on the preliminary lithological, biostratigraphic, paleomagnetic, dating, geochemical, and microbiological data, we conclude that expedition 347 accomplished most of the objectives that we had outlined in IODP proposal 672. This was indeed a successful expedition.

The full expedition report is available for download from http://publications.iodp.org/.

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A key continental archive for the last 2 Ma of climatic history of the central Mediterranean region: A pilot drilling in the Fucino Basin, central Italy

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Abstract. An 82 m long sedimentary succession was retrieved from the Fucino Basin, the largest intermountain tectonic depression of the central Apennines. The basin hosts a succession of fine-grained lacustrine sediments (ca. 900 m-thick) possibly continuously spanning the last 2 Ma. A preliminary tephrostratigraphy study allows us to ascribe the drilled 82 m long record to the last 180 ka. Multi-proxy geochemical analyses (XRF scanning, total organic/inorganic carbon, nitrogen and sulfur, oxygen isotopes) reveal noticeable variations, which are interpreted as paleohydrological and paleoenvironmental expressions related to classical glacial–interglacial cycles from the marine isotope stage (MIS) 6 to present day. In light of the preliminary results, the Fucino sedimentary succession is likely to provide a long, continuous, sensitive, and independently dated paleoclimatic archive of the central Mediterranean area.

1 Introduction

Understanding the spatio-temporal variability, the magnitude, and the different expressions of Quaternary orbital and millennial-scale paleoclimatic changes across regions is a frontier challenge of modern paleoclimatology (e.g. EPICA community members, 2006). Addressing this issue requires the acquisition of regionally representative high-resolution and well-dated records of climatic variability.

In this framework, the Fucino paleolake in central Italy (Fig. 1a) should add a nodal point in the western, currently vacant area of a network of long terrestrial Mediterranean records (including e.g. the Dead Sea (Neugebauer et al., 2014), Lake Van (Litt and Anselmetti, 2014), Lake Ohrid (Wagner et al., 2009), and the Tenaghi Philippon (Pross et al., 2015)). Indeed, among the central Italy intermountain tectonic depressions, it is probably one of the oldest and the only one that hosts a continuous, lacustrine succession since the late Plio–Quaternary (Fig. 1b). The site is also ideal because of its proximity to Quaternary peri-Tyrrhenian volcanic centres (Fig. 2) that on occasion deposited tephras in the basin that serve today as important chronological marker beds (e.g. Giaccio et al., 2012, 2015; Regattieri et al., 2015). This is a crucial requirement for comparing intra- and inter-regional

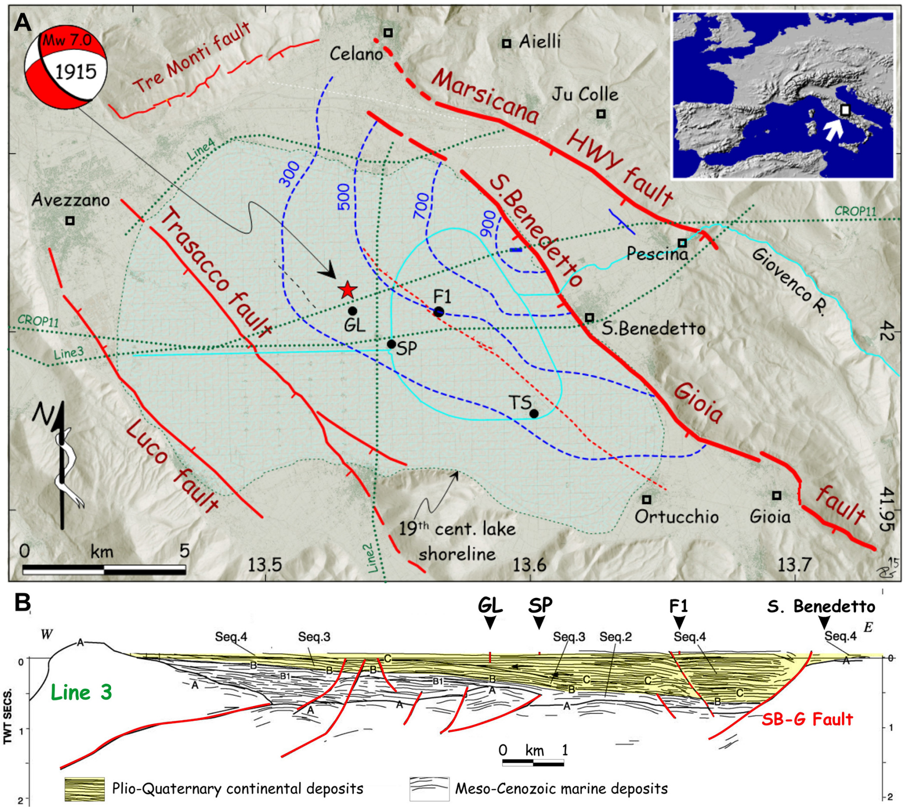

Figure 1. Reference map of the Fucino Plain with a representative seismic line. **(a)** Shaded relief of the Fucino Plain showing the location of the GeoLazio (GL), Telespazio (TS), Strada Provinciale 20 (SP) and Fucino 1 and 3 (F1–3; this study) boreholes. Dashed blue lines are the isochrones (in ms) of the Plio–Quaternary basin infilling with respect to the Quaternary master faults (red bold lines) responsible for the asymmetrical (half-graben) basin geometry. Dotted green lines are the traces of the available seismic lines. **(b)** Seismic line 3 (see trace in panel **a**) showing the internal architecture of the Plio–Quaternary continental deposits of the Fucino Basin along a W–E-oriented profile. The projected location of the GL, SP, and F1–3 boreholes is also shown. A, B, C: main unconformities; Seq. 2: Messinian foredeep sediments; Seq. 3: Pliocene fluvial and alluvial deposits; Seq. 4: Quaternary lacustrine and fluvial deposits. The figure and the information were compiled with some modifications from Cavinato et al. (2002), Galli et al. (2012), and Patacca et al. (2008).

paleoclimatic records, based on different dating methods, for evaluating the temporal relationship between them and with respect to the main climatic forcing (e.g. orbital).

With this purpose, an 82 m long core was recovered from the central eastern Fucino Basin (F1–3 in Fig. 1) in June 2015. The major goals of this drilling were to (i) collect a continuous record back to MIS (marine isotope stage) 6, (ii) assess the quality of the lacustrine sedimentary succession, (ii) explore the sensitivity of different paleoclimatic proxies, and (iii) document the presence of widespread tephras useful for regional to extra-regional correlation and their suitability for ^{40}Ar/^{39}Ar dating.

2 Geological setting and general background

The Fucino Basin (Fig. 1) is one of the largest intermountain depressions formed during the Plio–Quaternary extensional phase along the Apennine Chain (e.g. D'Agostino et al., 2001) within the earlier fold-and-thrust-belt system (e.g. Patacca and Scandone, 2007). Its opening was mainly driven by a major 110–130° N trending fault system (Galadini and Galli, 2000; Fig. 1a), which led to the formation of a typical half graben with up to ∼ 900 m of thick Quaternary deposits in the hanging wall of the master faults (Cavinato et al., 2002; Fig. 1b). Prior to the drainage, undertaken first by Romans in 1st century AD and then at the end of the 19th century (e.g. Galadini and Galli, 2001), the Fucino Basin hosted the largest lake (∼ 150 km^2, 20 m maximum water depth) of peninsular Italy.

In the past decades, several cores were drilled in the Fucino Basin for scientific and geotechnical purposes (Fig. 1). A preliminary palynological study of the 200 m long GeoLazio core (GL in Fig. 1) led to the conclusion that the upper 65 m of the succession would span the last 130 ka (Follieri et al., 1986). However, the dating of a thick tephra layer at ∼ 101 m depth yielded an age of 540 ± 9 ka (Follieri et al., 1991), hardly compatible with this chronological framework. Later, Narcisi (1994) analysed two foiditic tephra occurring

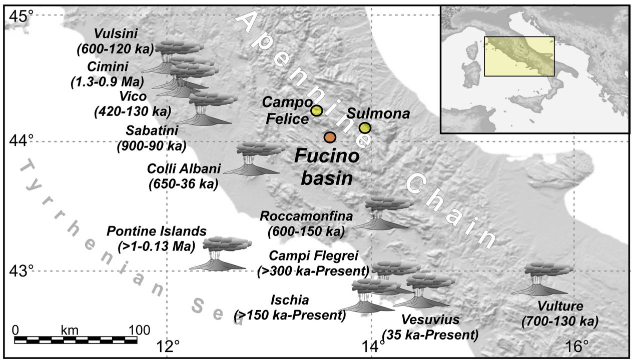

Figure 2. Location of the Fucino Basin with respect to the main volcanic districts of central and southern Italy (age in brackets represent the interval of volcanic activity). It is in a good range of distance with respect to the Quaternary tephra sources and in a favourable position with respect to the prevailing eastward direction of the stratospheric winds and hence for tephra dispersion. The locations of Sulmona and Campo Felice are also shown.

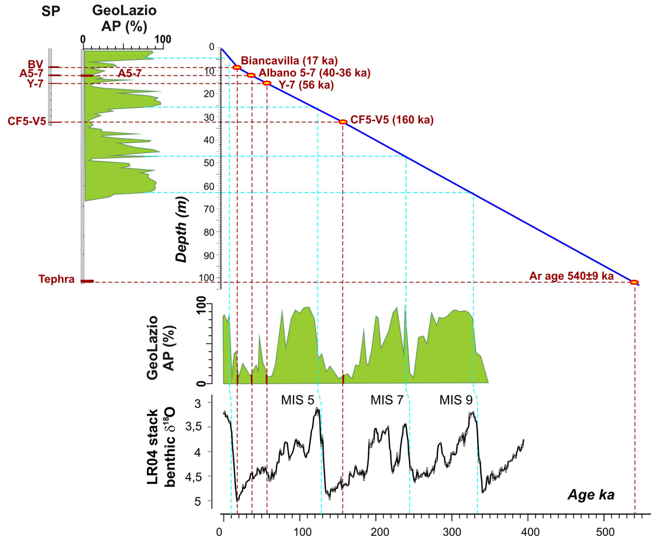

Figure 3. Revised depth–age curve for the GeoLazio arboreal pollen (AP) profile (Follieri et al., 1986) based on the recognition of marker tephra layers in core SP (Fig. 1) and on the dating of the layer at ~101 m of depth in core GeoLazio (Follieri et al., 1991). After revision, the resulting AP curve shows a variability, which correlates quite well the benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005) from MIS 9 to today.

in the GeoLazio and Telespazio cores (TS in Fig. 1), at ~ 12–14 m depth, which, on the basis of their peculiar glass major element composition, were attributed to the eruptive units Albano 5–7 (Giaccio et al., 2007), from a cluster of Colli Albani eruptions dated between 40 and 36 ka (Giaccio et al., 2009). Finally, the tephrostratigraphic study of a 30 m deep borehole (SP in Fig. 1a) drilled close to the GeoLazio site, and in a comparable range of the isochrones of the Quaternary infill (Fig. 1a), allowed for the recognition of some relevant tephra markers spanning between ca. 18 and ca. 160 ka (Authors' unpublished data; Fig. 3). All of these chronological constraints lead us to a reinterpretation of the chronology of the GeoLazio pollen record, spanning the MIS 1–9 interval, suggesting that the Fucino succession extends continuously at least back to ~ 540 ka (Fig. 3).

3 Material and methods

3.1 Drilling site selection and procedure

The drilling site was selected using an evaluation of sedimentation rate obtained from the new interpretation of the GeoLazio pollen profile (Fig. 3) and the general sedimentary–tectonic architecture of the basin (Fig. 1). With the aim to recover a record spanning back into MIS 6, we selected an area located some kilometres eastward from the GeoLazio and SP core sites, i.e. toward the depocentre where the isochrones are deeper (Fig. 1). Therefore, this site provided us the opportunity of recovering a succession more expanded than the GeoLazio core.

At the selected site (42.00° N, 13.56° E), two parallel cores were recovered. The first hole (F1) was drilled down to a field depth of 75 m and the second hole (F3) down to 56.25 m. The length of the single recovered core section was 1.5 m, with an overlap of 75 cm between the two holes, in order to obtain a complete sedimentary succession for the upper part of the sequence. Samples from core catchers were taken directly in the field, whereas the rest of the cores were stored in a dark and cool place for further analyses.

3.2 Laboratory work

3.2.1 Lithological analyses and XRF scanning

Core opening and core description was carried out at the laboratory of the University of Cologne, Germany. Immediately after core opening, a surface scan of each core section was carried out with a line scan camera from an Itrax core scanner (Cox, Sweden). Further analyses included XRF (X-ray fluorescence) scanning carried out with a chromium (Cr) X-ray source at 30 kV and 55 mA at 2.5 mm resolution and 10 s integration time.

3.2.2 Geochemical analyses on core catcher material

Total carbon (TC), total inorganic carbon (TIC), total nitrogen (TN), total sulfur (TS), and stable oxygen isotope compositions were carried out on discrete samples from the top of each core catcher. Samples were dried in an oven at 50 °C. After disaggregation and sieving, the fraction below 100 µm was powdered and homogenized for geochemical analyses.

Stable isotope analyses were performed on samples with > 20 % carbonate content using a GasBench II (Thermo Scientific) coupled to a Delta XP IRMS (Finnigan) at the In-

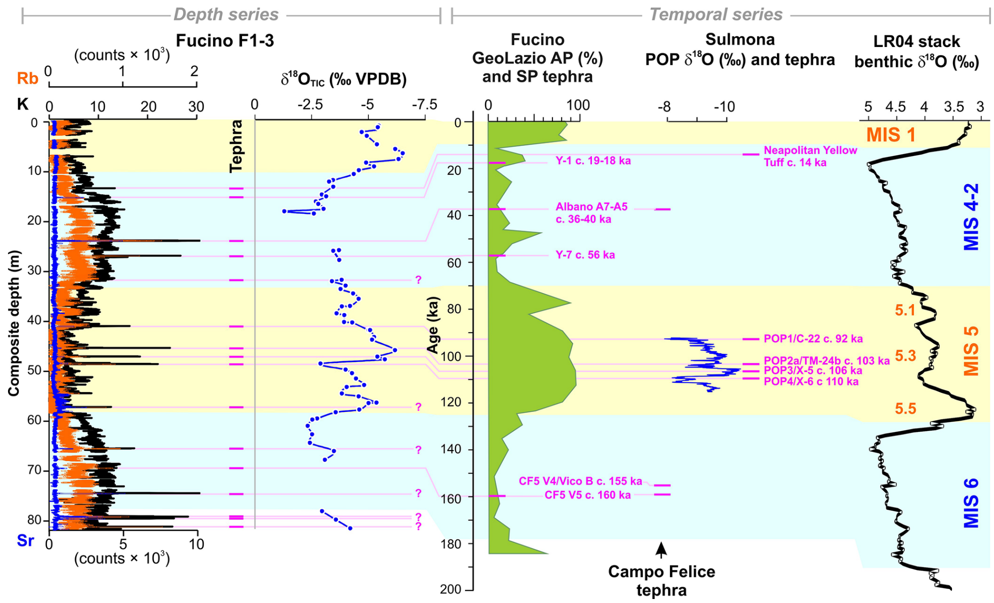

Figure 4. Provisional tephrochronological framework of the Fucino F1–3 composite stratigraphy. The provisional correlation of some of the F1–F3 tephras – which are also depicted by peaks in K, Rb, and Sr – has been tentatively established on their stratigraphic order and lithological features compared to the tephra successions from the local cores of Fucino SP and the chronologically recalibrated GeoLazio and cores from the surrounding basins of Campo Felice (Giraudi and Giaccio, 2015) and Sulmona (Giaccio et al., 2012; Regattieri et al., 2015) (Fig. 2).

stitute of Geosciences and Earth Resources of the Italian National Research Council (IGG-CNR) of Pisa (Italy). Carbonate samples of ∼ 0.15 mg of total $CaCO_3$ were dissolved in H_3PO_4 (100 %) for 1 h at 70 °C. All the results are reported relative to the V-PDB (Vienna Pee Dee Belemnite) international standard and corrected using the international standards NBS-18 (National Bureau of Standards) and a set of three internal standards. The analytical uncertainties for $\delta^{18}O$ and $\delta^{13}C$ are 0.17 and 0.15 ‰ respectively. TN and TS were determined with a vario Micro cube combustion CNS elemental analyser (Elementar, Germany) after combustion at 1150 °C at the University of Cologne, Germany. TC and TIC were measured with a DIMATOC 200 (DIMATEC, Germany) at the University of Cologne, Germany. TOC was calculated by subtracting TIC from TC.

4 First results and preliminary discussion

Both cores are composed of grey lacustrine calcareous marl, with a variable proportion of clay. A preliminary 82 m long composite succession is based on visual correlation after core opening and using the line scan images from the Itrax core scanner (Cox Analytical, Sweden) and the Corewall software package (Corelyzer 2.0.1). Core sections that looked disturbed from the coring process were not included in the core composite. Although, theoretically, the drilling depths should have avoided gaps between the individual runs in each hole, overlapping sequences in the lower part of the F3 hole indicated gaps of around 20 cm between the individual runs of the F1 hole due to core expansion after recovery. We therefore assumed 20 cm gaps between the F1 sequences, where there were no overlapping F3 sequences; i.e. for the depths > ∼ 55 m. Based on the core composite stratigraphy, Ca, K, Ti, Rb, and Sr data from XRF scanning were compiled to produce an overview profile.

At least 16 centimetric to decimetric thick and relatively coarse-grained tephra layers were identified along the composite core, several of which are also clearly marked by prominent spikes in K, Rb, and Sr (Fig. 4). A provisional correlation of some of the tephras has been tentatively established based on their stratigraphic order and lithological features (e.g. overall tephra colour, thickness, grain size, assortment of the mineral and lithic components, and colour and shape of the juvenile clasts) compared to the local tephra successions from the Fucino core SP and the chronologically recalibrated GeoLazio core (Fig. 3) and cores from the surrounding basins of Campo Felice (Giraudi and Giaccio, 2015) and Sulmona (Giaccio et al., 2012; Regattieri et al., 2015) (Figs. 3, 4). Although the lack of robust geochemical data renders it premature to propose an age model based on tephrochronology alone, general tephrostratigraphic consistency allows us to ascribe the investigated successions to the MIS 6–1 period. The resulting sedimentation rate would range between ∼ 0.3 and 0.6 mm a^{-1}, with a mean of ∼ 0.45 mm a^{-1}, which is substantially higher than that of the GeoLazio/SP succession (∼ 0.2 mm a^{-1}; Fig. 3).

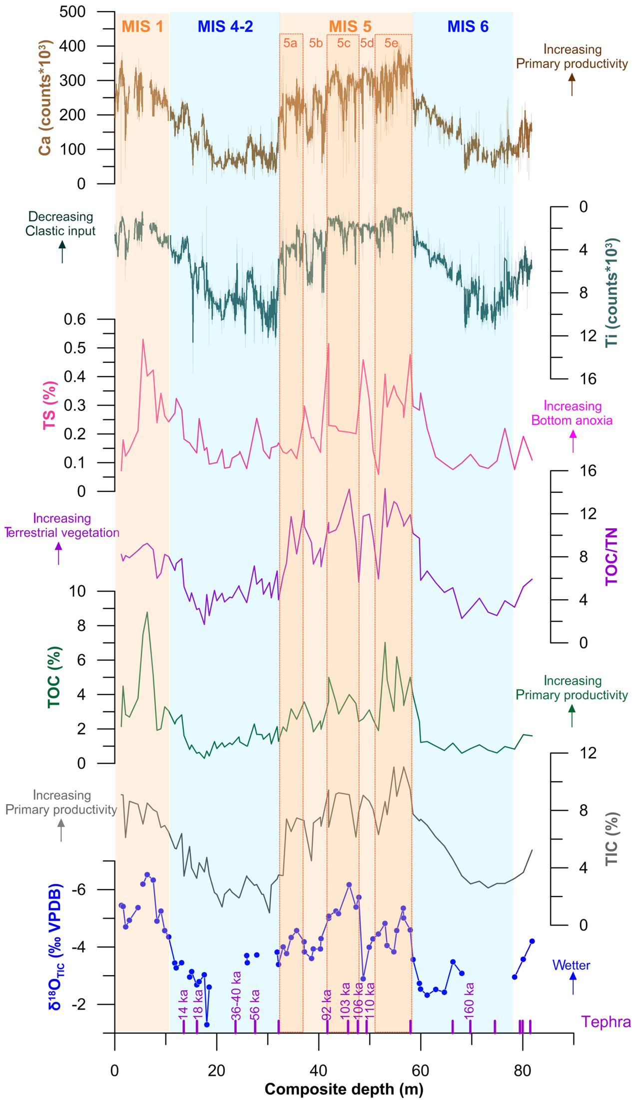

Figure 5. Proxy series plotted on preliminary composited depth. From bottom, provisional age control points based on the supposed recognition of the tephra layers as shown in Fig. 4: $\delta^{18}O_{TIC}$, total inorganic carbon (TIC %), total organic carbon (TOC %), TOC / TN ratio, total sulfur (TS %) (all from the same core catcher samples), and Ti and Ca from XRF scanning; thick lines are 20 pt running averages, note that the Ti scale is reversed. Blue/pink shadowing indicates marine isotope stages (MIS) following the correlation proposed in Fig. 4. The provisional sub-stage subdivision of the MIS 5 is also shown.

Geochemical and biogeochemical analyses from core catcher material show significant variability, with major trends consistent between the different proxies and with XRF data for Ca and Ti (Fig. 5). There is a strong ($r = 0.95$) negative correlation between Ca and Ti. Due to this strong anti-correlation and to the fact that Ca and TIC depth series show nearly identical patterns of variation, we assume that both proxies are mainly related by authigenic (i.e. biomediated) precipitation of calcite. The amount of calcite in the sediments depends on lake primary productivity, temperature, the input of Ca from the catchment (e.g. Gierlowsky-Kordesh, 2010; Vogel et al., 2010), and the preservation of calcite as a function of organic matter (OM) decomposition and bacterial CO_2 release in the bottom waters (e.g. Müller et al., 2006). Also, TOC is mainly a function of changes in organic production in the lake and of changes in catchment vegetation (Leng et al., 2013), and, along with TIC, it tends to be higher during warmer and wetter periods (i.e. interglacials/interstadials). During these periods, calcite (TIC $\times$ 8.33) and organic matter (TOC $\times \sim 2.5$) derived from TIC and TOC may form up to $> 90\%$ of the total sediments (Fig. 5). This suggests the negligible contribution of clastic, minerogenic input from catchment erosion and is consistent with the low Ti concentration (e.g. Vogel et al., 2010). $\delta^{18}O_{TIC}$ of most Mediterranean lakes is instead considered a proxy for the balance of precipitation vs. lake evaporation (e.g. Roberts et al., 2008), with higher or lower values related to decreasing or increasing moisture conditions, respectively.

The TOC / TN ratio is often related to the source of the OM and generally reflects the proportion of aquatic (macrophytes and phytoplankton) vs. terrestrial plants, with higher values indicating prevailing allochthon (terrestrial) input for the OM (Meyers and Ishiwatari, 1995), i.e. enhanced development of vegetation in the lake catchment. However, some sections in the core indicate TOC / TN ratios as low as ~ 2 (Fig. 5). As this is too low for natural substances, selective decomposition of OM could have taken place and may have affected the TOC / TN ratio. In addition, very low amounts of TOC or TN, which are close to the detection limits, may have biased the TOC / TN ratio. TS is related to variations in OM production and in redox conditions within the lake. In our record, the high positive correlation between TS and TOC ($r = 0.70$) and their similar patterns suggest that higher S values are related to the development of anoxic conditions at the bottom of the lake due to increasing productivity and/or lake stratification.

Based on their paleoclimatic/paleoenvironmental significance, the consistent variations in all of the presented proxies (Fig. 5) perfectly match the timescale proposed by the preliminary tephrochronological framework (Fig. 4). Indeed, lower precipitation (higher $\delta^{18}O_{TIC}$), reduced lake productivity (lower TIC, TOC, and TS), contraction of terrestrial vegetation (lower TOC / TN ratio), and increase in catchment erosion (higher Ti) correspond to the colder glacial conditions of the MIS 6 and MIS 4–2 (Fig. 5). During the glacial part of the MIS 5 and the interglacial MIS 5.5 and MIS 1, warmer and wetter climate conditions, promoting primary productivity and vegetation development, are instead apparent. Interestingly, although the temporal resolution of the proxy obtained from the core catcher ($\delta^{18}O$, TIC, TOC, TOC / CN, and TS) is very low (~ 2 ka, based on the preliminary estimation of the sedimentation rate of ca. 0.45 mm a^{-1}) the interstadial/stadial pattern during the MIS 5 is also recorded by con-current variations in all the investigated proxies (Fig. 5). This notion is corroborated also by the similarities of the Fucino record with the high-resolution oxygen isotope time series from the Sulmona Basin (Regattieri et al., 2015, Fig. 4). Indeed, although the two series are correlated only by means of the preliminary tephrostratigraphic analyses (Fig. 4), across the four presumably common tephras, the F1–3 $\delta^{18}O_{TIC}$ profile seems to show the same pronounced millennial-scale fluctuations documented in the Sulmona record (Fig. 4).

5 Conclusions

The first multiproxy analyses performed on the newly acquired 82 m long core from Fucino lake sediments, along with the reinterpretation of the previous data, suggest that

i. the entire lacustrine succession in the Fucino Basin extends continuously at least up to ∼ 540 ka and, by extrapolating the sedimentation rate (0.4–0.5 mm a^{-1}) to the maximum depth of ca. 900 m, possibly 2 Ma back ;

ii. the Fucino sediments include several tephra layers from the surrounding peri-Tyrrhenian volcanic centres, most of which are suitable for both indirect (geochemical fingerprinting) and direct ($^{40}Ar/^{39}Ar$) dating;

iii. the geochemical and biogeochemical properties alongside the pollen record suggest a high sensitivity of the Fucino lacustrine sediments to the climatic and environmental changes.

In order to explore the full potential of the Fucino succession, further investigations, including detailed tephra analyses, ^{14}C and $^{40}Ar/^{39}Ar$ geochronology, and high-resolution biogeochemical, stable isotope, paleontological, and paleomagnetic analyses are in progress. Nevertheless, the present preliminary results make the Fucino Basin a good candidate for a deep-drilling project, which could provide one of the longest continuous records for studying, at both orbital and millennial scale, the Quaternary paleoclimatic history of the central Mediterranean area, possibly 2 Ma back.

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Progress Reports

The Volta Grande do Xingu: reconstruction of past environments and forecasting of future scenarios of a unique Amazonian fluvial landscape

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Abstract. The Xingu River is a large clearwater river in eastern Amazonia and its downstream sector, known as the Volta Grande do Xingu ("Xingu Great Bend"), is a unique fluvial landscape that plays an important role in the biodiversity, biogeochemistry and prehistoric and historic peopling of Amazonia. The sedimentary dynamics of the Xingu River in the Volta Grande and its downstream sector will be shifted in the next few years due to the construction of dams associated with the Belo Monte hydropower project. Impacts on river biodiversity and carbon cycling are anticipated, especially due to likely changes in sedimentation and riverbed characteristics. This research project aims to define the geological and climate factors responsible for the development of the Volta Grande landscape and to track its environmental changes during the Holocene, using the modern system as a reference. In this context, sediment cores, riverbed rock and sediment samples and greenhouse gas (GHG) samples were collected in the Volta Grande do Xingu and adjacent upstream and downstream sectors. The reconstruction of past conditions in the Volta Grande is necessary for forecasting future scenarios and defining biodiversity conservation strategies under the operation of Belo Monte dams. This paper describes the scientific questions of the project and the sampling surveys performed by an international team of Earth scientists and biologists during the dry seasons of 2013 and 2014. Preliminary results are presented and a future workshop is planned to integrate results, present data to the scientific community and discuss possibilities for deeper drilling in the Xingu ria to extend the sedimentary record of the Volta Grande do Xingu.

1 Introduction

The Xingu River is the third largest tributary of the Amazon River and the second largest clearwater river system in South America. Its downstream reach comprises an anomalous bedrock anastomozing system (Wohl and Merritt, 2001) known as the Volta Grande do Xingu ("Xingu Great Bend"). The channel morphology of the Xingu River in the Volta Grande is characterized by multiple flow-path channels with rapids flowing over fractured basement rocks. The tremendous size and morphological complexity of the rapids, combined with a high variation in water level between the dry and wet seasons, make the Volta Grande do Xingu a unique environment for Amazonian biodiversity (Zuanon, 1999; Camargo et al., 2004; Acselrad et al., 2009; Camargo and Ghilardi, 2009; Nogueira et al., 2010). Compared to other Amazonian rivers, the Xingu River also stands out due to its relatively high spatial and temporal variability in methane emissions (Sawakuchi et al., 2014) and changes in land use as a result of historic and prehistoric settlements (Heckenberger et al., 2003).

The main channel of the Volta Grande has been impounded and will be partially diverted for operation of the Belo Monte hydropower plant (Fearnside, 2006; Sousa and Reid, 2010; Sabaj Pérez, 2015), its construction expected to be complete during the second half of 2016. That project has prompted great debate surrounding the tradeoffs between energy generation and socioenvironmental impacts. The seasonal water level variation and flood pulse in the Volta Grande do Xingu will be determined by the dam's operation and energy production. Changes in river substrate and loss of environmental diversity are expected under the Belo Monte scenario. The trapping of sediments upstream and decrease in the water flow downstream of the impoundment dam will negatively affect biodiversity through the loss of various river substrates and benthic habitats. The trapping of fine-grained sediment in the in-stream and off-stream reservoirs can stimulate the production of greenhouse gases (GHG). The shift from bedrock/sand to mud substrates is expected to increase GHG emissions, based on comparisons of CH_4 emissions from the Xingu rapids and the ria sectors (Sawakuchi et al., 2014). Also, agricultural activities have increased deforestation rates in the Xingu River catchment during recent decades, which will favor runoff and will improve hydropower generation in the short term, but may reduce hydropower potential in the long term as a result of lower precipitation throughout the catchment (Stickler et al., 2013). The possible negative feedback response of the lower Xingu to deforestation and hydropower projects requires urgent attention. Reconstruction of past hydrology, sediment supply, vegetation and ecological conditions in the Xingu catchment is critical to evaluate the long-term state and sensitivity of the Xingu River and analogous clear waters such as the Tapajós and Tocantins rivers, especially in the context of global climate change and regional anthropogenic disturbance. The characterization of past changes in vegetation and sedimentation rates allows one to track drought and flood events and their impacts on the Volta Grande ecosystem. Understanding changes in river substrate induced by anthropogenic or natural changes in hydrology is important because riverbed characteristics play a key role in aquatic ecology and GHG production.

This project comprises a multidisciplinary research team working to improve knowledge on the origin of the Volta Grande do Xingu, the reconstruction of its Late Quaternary changes in vegetation, hydrology and biogeochemistry, and related effects on biodiversity. Additionally, we expect that a better understanding of the fluvial dynamics of the Volta Grande do Xingu on scales from hundreds to thousands of years before present will yield valuable insights to forecast future environmental scenarios. The Belo Monte Dam complex will directly affect the Volta Grande by flooding approximately 382 km^2 over an 80 river km stretch of the Xingu channel, and dewatering another 90 river km below the impoundment dam with a reduction in flood pulse magnitude and variability (Sabaj Pérez, 2015). Tracking past changes in the Xingu River flow will establish natural baselines to evaluate future environmental changes due to the Belo Monte. In this context, sediment cores were collected in the Xingu ria and floodplain lakes of the Volta Grande. Riverbed rock and sediment samples and GHGs emitted from the river channel and areas that will be flooded by the Belo Monte dams were collected to characterize the Volta Grande do Xingu before the dam's operation. This report presents the questions that motivated the project, the location and characteristics of sediment cores, and preliminary data obtained after sampling.

2 Site description

The Xingu is an Amazonian clearwater river (Sioli, 1985), with a bedload dominated by fine to coarse sand, low suspended load and neutral to slightly alkaline waters (pH approximately 7.3). After the confluence with the Iriri River, the Xingu flows NE and bends 90° at the transition between the Amazon craton basement and the Amazon sedimentary basin (Fig. 1). After flowing to the SE for around 60 km, the Xingu bends 90° again to the NE. It continues to flow over basement rocks for another 60 km until its last 90° bend, where it crosses the sedimentary rocks at the border of the Amazon basin. Those three sequential 90° bends form the Volta Grande do Xingu and compose an exceptionally complex planform that is unique among large tropical rivers. In this sector, the Xingu is a bedrock river characterized by a 4–5 km wide channel segmented into multiple interconnected crisscross channels with rapids bounding sediment bars covered by riparian vegetation and rainforest. The origin of

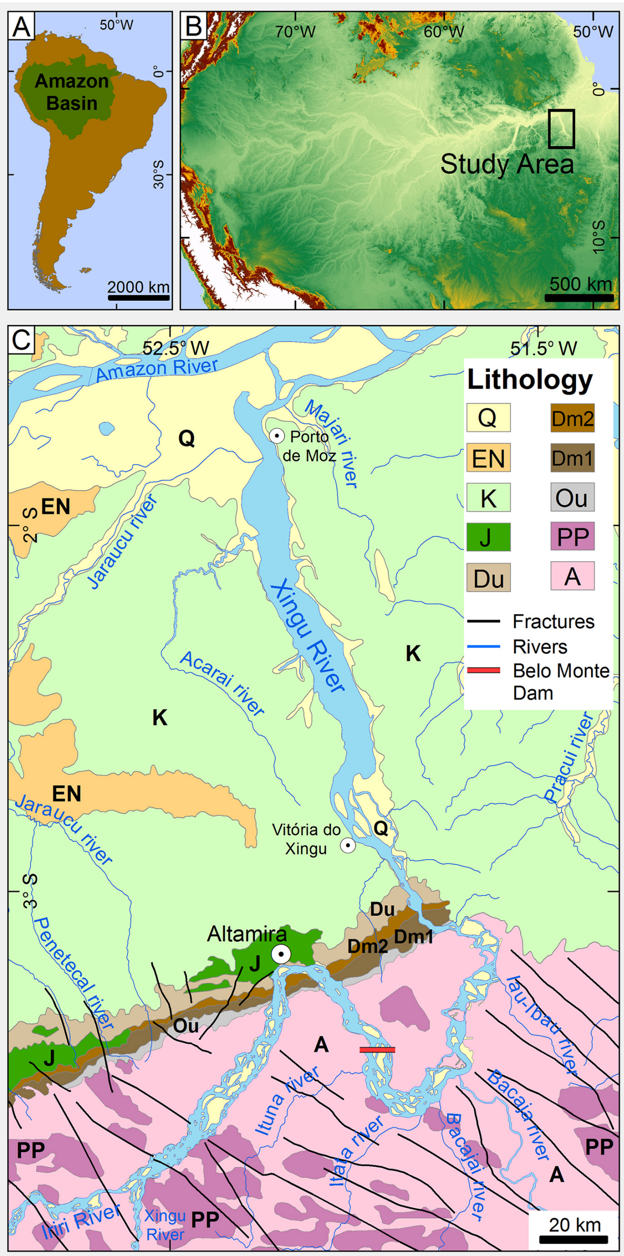

Figure 1. Simplified geological map of the Volta Grande do Xingu and Xingu ria, eastern Amazonia (Bahia et al., 2004). Lithologies: (A) Archean gneisses, granodiorites and granitoids (Xingu complex) and metavolcanic and metasedimentary rocks; (PP) intrusive suites: Paleoproterozoic granites, granodiorites and charnockites; (Ou) Ordovician–Devonian organic-rich shales and sandstones (Trombetas group); (Dm1–Dm2–Du) Middle–Upper Devonian shales, siltstones and sandstones (Urupadi and Curuá groups); (J) Triassic–Jurassic diabase (Penatecaua formation); (K) Alter do Chão formation: sandstones and conglomerates; (EN) Eocene–Neogene undifferentiated sediments and laterite crusts; (Q) undifferentiated Quaternary sediments. The red bar indicates the position of the main Belo Monte dam (Pimental site).

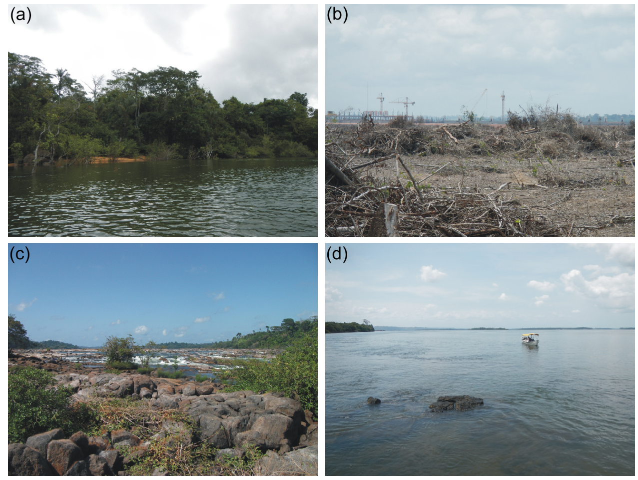

Figure 2. **(a)** Stabilized sediment bar (island) covered by forest vegetation nearby the Pimental dam site. **(b)** Deforested sediment bar to be flooded by the Belo Monte reservoir. Picture from island adjacent (upstream) to the Pimental dam site. **(c)** Rapids in the downstream sector of the Volta Grande. **(d)** Xingu ria downstream of the Volta Grande. Pictures taken during the dry season (November 2014).

this particular channel morphology is still under debate. The Xingu flows as a bedrock-dominated river until it enters the Amazon sedimentary basin through a singular channel about 0.5 km wide at its narrowest point and up to 80 m deep (Sabaj Pérez, 2015). At the transition, it suddenly drops from elevations of 60–90 to 5–20 m and shifts to a lowland Amazonian river with a single slack water channel under the influence of tides (the "Xingu ria"). The Xingu ria channel can reach up to 14 km in width, flowing straight for about 180 km until it reaches the Amazon River. The upstream sector of the Xingu ria is occupied by a complex of stabilized bars, the Tabuleiro do Embaubal archipelago, which is formed by the trapping of sands that bypass the Volta Grande. Figure 2 shows some fluvial landscapes characterizing the Xingu River within the studied sector.

3 Scientific questions

This project deals with the characterization of the present sedimentary dynamics and reconstruction of past environmental conditions of the Volta Grande during the Quaternary. The description of the present state of the Volta Grande will provide a reference scenario to track past environmental changes. It is also a fundamental exercise to evaluate future changes due to the Belo Monte Dam complex. The reconstruction of paleogeography, paleovegetation and paleohydrology will shed light on how the Volta Grande do Xingu achieved its present geomorphological and ecological complexity, allowing us to evaluate the long-term variability of river dynamics. The main scientific questions motivating this project are the following.

A. What is the age of the rapids of the Volta Grande? The rapids of the Volta Grande do Xingu play a major role in aquatic diversity and endemism, particularly for fishes. The uplift and exhumation histories of the bedrock channels will be studied at multiple timescales through cosmogenic nuclides (^{10}Be) measured in sediments and bedrock and (U-Th)/He and fission track thermochronometry in apatite retrieved from basement samples in the Volta Grande and from dikes and sills cutting through sedimentary rocks farther to the north, in the Amazon sedimentary basin domain. Surface exposure ages of rapids and waterfalls, as well as catchment erosion rates, will be determined through ^{10}Be measurements. Thermochronometry techniques will reveal the age and rates of rock exhumation from depths less than 1–4 km. By comparing differences in exhumation rates in different localities, a minimum age for potential differential uplift along the Volta Grande will be constrained. This information is a critical step towards assessing how and when the Volta Grande achieved its rich and endemic diversity of rheophilic fishes and other aquatic organisms.

B. What effect did Quaternary precipitation changes have on river sediment supply? Changes in sediment composition and sedimentation rate through time will be compared with the precipitation changes in the South American Monsoon System (SAMS). This will allow us to evaluate the response of fluvio-hydrological variables such as water turbidity and river level seasonality to Quaternary climate changes. Age models to constrain environmental indicators (e.g., geochemistry, environmental magnetism) will be supported by ^{14}C and optically stimulated luminescence (OSL) dating. The reconstruction of the sediment supply through time also affords insights into shifts in channel morphology, especially with regards to the building and erosion of sediment bars covering bedrock within the rapids.

C. How did riparian vegetation respond to Holocene climatic and anthropogenic changes? Various palynological studies carried out in Amazonia suggest that during the Late Holocene, drought episodes and human interference in the landscape were non-uniform in time and space, suggesting that the period may have been unusually dynamic with respect to climate (Bush et al., 2014). Other studies also point to evidence of increase in frequency of anthropogenic and climate-related fires, with significant changes in vegetation (McMichael et al., 2012a, b). Archaeological evidence suggests that human settlement of the Xingu River catchment dates to the Middle Holocene (e.g., Silva and Rebellato, 2003). *Terra Preta de Índio*, pottery and petroglyphs are widespread along river banks of the Xingu, including the Volta Grande site. Changes in land use for agriculture and mining activities have intensified in the Xingu catchment during the last several decades. Thus, the history of human occupation of eastern Amazonia and changes in vegetation induced by anthropogenic activities over the last decades to few millennia could be recorded in sediments from floodplain lakes and from the Xingu ria. We expect to generate a high-resolution record of paleovegetation and sedimentation rates for tracking of decadal to millennial anthropogenic and climate changes in the Xingu River catchment.

D. How do the carbon budget and GHG emissions respond to changes in sediment supply and river level? Riverbed sediment type, suspended sediment concentration and changes in water depth throughout the year can drastically influence GHG emissions from Amazonian rivers. The lower Xingu River (ria sector) has the greatest CH_4 flux among the main Amazon River tributaries (Sawakuchi et al., 2014). Thus, a significant share of the CH_4 flux from the future reservoirs might be attributed to the previous natural river emission, compensating for the emission from impounded water to some extent. On the other hand, bacteria in oxic soils tend to consume atmospheric CH_4, and after flooding those soils become an important hotspot of CH_4 production fueling the reservoir. Although hydroelectric reservoirs generally have lower carbon emission per energy production than thermal energy supply (Ometto et al., 2013), such reservoirs are far from neutral for GHG emissions (Almeida et al., 2013). Nevertheless, most of the available information regarding GHG emissions from reservoirs does not take into account the natural emissions of GHG from the running river and soil consumption before flooding. CH_4 and CO_2 flux measurements from rivers and soil in areas directly affected by the Belo Monte reservoirs, before impoundment, were performed to serve as a baseline to track future changes in fluxes caused by the reservoirs. The Xingu ria is considered a depositional system analogous to the Belo Monte hydroelectric reservoirs. In this way, CH_4 production and flux within muddy sediments from the Xingu ria are well suited to inform decadal to millennial changes in GHG emissions and carbon budget due to changes in the water column and riverbed. Deposition rates, carbon concentration and GHG concentrations measured in sediment cores of the ria sector provide constraint values on how substrate changes in the reservoirs will affect carbon sink and GHG production and emission over decadal to millennial timescales.

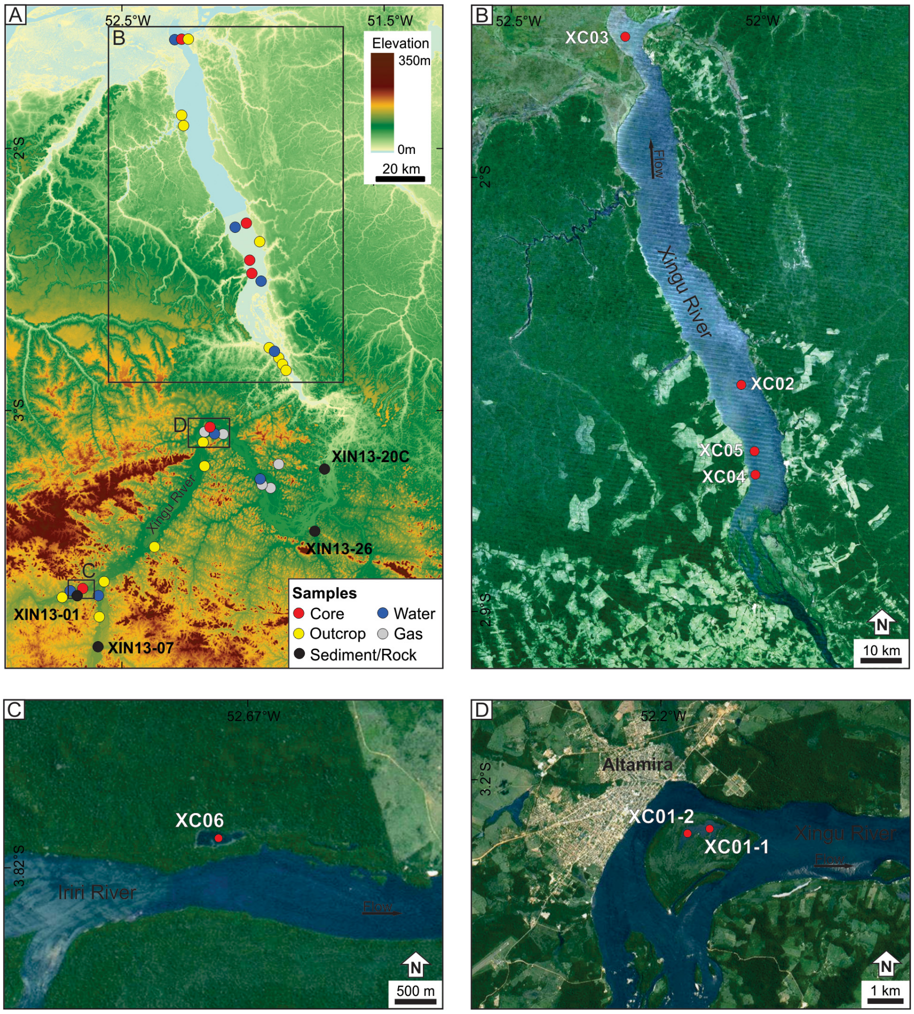

Figure 3. **(a)** Location of sediment cores (XC01 to XC06), surface sediments, rock and gas samples retrieved in the Volta Grande do Xingu and the Xingu ria. Elevation data from SRTM. **(b, c, d)** Sediment cores were collected in the ria and floodplain lakes. Satellite images from Google Earth.

4 Sampling of sediment cores, riverbed rocks and greenhouse gases

Field surveys were performed during the dry seasons of 2013 and 2014. Sites for coring in the Xingu ria were selected based on water depth profiles coupled with riverbed sediment sampling. Cores were collected in deeper portions of the channel covered by muddy sediments. Deeper zones of perennial floodplain lakes and the Xingu ria were the targets for coring, since they represent accumulation sites characterized by relatively continuous deposition of fine-grained sediments throughout the year. Eight sediment cores were retrieved from the Xingu ria and from nearby floodplain lakes. Sediment cores were collected in water depths from 1 m (floodplain lakes) to 18 m (ria), the latter depths (ria) by divers. The cores were collected using PVC tubes of up to 6 m in length and percussion into the substrate. Samples of riverbed bedrock surfaces and sands were collected in rapids and waterfalls for determination of surface exposure ages, erosion rates and basement cooling and exhumation history. Parallel surveys by a team of ichthyologists will allow us to evaluate ecological relationships between fishes and riverbed characteristics. Floating chambers were used to measure CO_2 and CH_4 fluxes from the river channel and water samples were used to analyze gas concentration and stable carbon isotope ratio via headspace extraction (Sawakuchi et al., 2014). Static chambers were used to measure CO_2 and CH_4 fluxes from soil to atmosphere on stabilized bars and along river margins that will be flooded by the Belo Monte reservoir. Figure 3 shows the locations of sediment cores and surface sediment, rock and gas samples. Table 1 lists the water depth, retrieved sediment column and geographical coordinates of each sediment core.

Table 1. Sediment cores retrieved in the Xingu ria and floodplain lakes of the Xingu and Iriri rivers.

Setting	Core code	Water depth (m)	Retrieved sediment thickness (cm)	Latitude (deg.)	Longitude (deg.)
Xingu floodplain lake	XC01-1	1	200	−3.214142	−52.188714
	XC01-2	1	120	−3.214277	−52.190118
Xingu ria	XC02-1	13	300	−2.412991	−52.027668
	XC03	10	370	−1.708922	−52.279840
	XC04	18	516	−2.604619	−52.012447
	XC05	13	470	−2.556209	−52.016087
Iriri floodplain lake	XC06	1.5	230	−3.816163	−52.672267

5 Project development

5.1 Cosmogenic nuclides and landscape evolution

Sampled sediments from lateral bars in the Volta Grande (Fig. 3a) that were targeted for cosmogenic ^{10}Be analysis of catchment-wide average erosion rates were processed at the Desert Research Institute (quartz purification) and Dalhousie University (extraction of Be target material for AMS (accelerator mass spectrometry) as BeO) in 2014, following protocols adapted from Kohl and Nishiizumi (1992). BeO targets extracted from the samples were analyzed by ^{10}Be / ^{9}Be ratios at Lawrence Livermore National Laboratory. Estimated values for catchment-wide ^{10}Be production rates were calculated from averaging individual production obtained pixel-by-pixel and scaled by altitude in a 1 km DEM for the catchment above the sampling point (Table 2). We are currently refining that estimate by considering shielding by topography, but given the low relief of the area, it should not change the results by more than 1–2 %. Volta Grande denudation rates are of a similar order of magnitude compared to rates recorded for the Xingu further upstream, near São José do Xingu (the latter as published by Wittmann et al., 2011, and also based on recalculated rates using recent ^{10}Be production rate estimates; those values are shown in Table 2). Denudation rates along the Xingu main stem are 50 % higher than those from the tributaries (Iriri and Bacajaí rivers). We interpret the lower denudation rates for the Xingu tributaries as indicative of a stable landscape during the Late Pleistocene–Holocene for the specific region in the immediate vicinity of the Volta Grande. The apparent age or averaging period (von Blanckenburg, 2005) derived from the Iriri and Bacajaí samples is 70–100 ka (Table 2). The homogeneous and low (0.01 mm a^{-1}) denudation rates indicate that differences in landscape activity between the catchment upstream of Sao José do Xingu (Wittman et al., 2011) and upstream of the Volta Grande are not significant and that the present-day landscape configuration at the catchment scale probably has an age of several tens of thousands of years. A better understanding of denudation along outcrops in the Xingu main stem nevertheless will be given by bedrock samples that were taken at two different strath levels above the river level. Those two levels were sampled at different elevations above the main flow surface (i.e., relative to the 2013 September low stage flow) and at different points along the river. Analyses are still in progress and final AMS measurements will be performed following preparation of samples with an improved low ^{10}Be / ^{9}Be ratio carrier at the Desert Research Institute during 2015. The results will help us to further check whether the landscape as a whole is relatively old (similar, high ^{10}Be concentrations on both landscape and bedrock surfaces, suggesting saturation; cf. Lal, 1991) or whether younger surfaces appear in certain landscape positions showing recently abraded or plucked bedrock portions at lower ^{10}Be concentrations (Fujioka et al., 2015). If ^{10}Be bedrock concentrations are low enough (i.e., an order of magnitude less than overall sand concentrations), we will attempt to measure in situ cosmogenic ^{14}C in the quartz we have already purified. This will allow for the analysis of potentially young (i.e., Late Quaternary) erosion events in the main stem via a paired isotope study (e.g., Hippe et al., 2014). It must be noted that the ^{10}Be bedrock study by itself does not intend to provide direct ages for bedrock exposure, but rather acts as a guide to implement subsequent tests. An apatite fission track and (U-Th)/He thermochronology will be used to constrain older landscape evolution events recorded in the Volta Grande.

5.2 Fish diversity and riverbed complexity

The morphology and composition of Xingu River substrates are extremely important for aquatic ecology and biodiversity. The Volta Grande is dominated by substrates consisting of fractured bedrocks, iron oxide crusts, gravels and sands. Iron oxide crusts allow for the formation of complex morphologies in the riverbed. The Xingu ria has a more homogeneous riverbed mainly covered by organic-rich mud, with sand deposition in the ria head and on the shallow marginal portions of the channel. The substrate complexity in the Volta Grande offers more niche space, and is hypothesized to be a driver of diversity among rheophilic fishes in the Volta Grande compared to the Xingu ria. An old and stable system of clearwater and complex braids with rocky rapids might account for the exceptionally diverse fish fauna, especially with respect

Table 2. Fluvial sand ^{10}Be concentration and calculated catchment-wide average denudation rates for catchments above sampling points in the Xingu River and the Iriri and Bacajaí tributaries. Production rates obtained by averaging pixel-by-pixel the production rates calculated according to the Lal (1991) and Stone (2000) scaling scheme, using the global production rate in Heyman (2014). Full data set given only for samples measured in this study. For comparison of final results, we also present the final ^{10}Be data by Wittmann et al. (2011). AMS ^{10}Be / ^{9}Be ratio for the blank: $2.019 \pm 0.425 \times 10^{-15}$. Standard used for normalization 07KNSTD3110, with a ^{10}Be / ^{9}Be ratio of 2.85×10^{-12}. Samples measured after adding a Be carrier solution of density 1.013 g mL^{-1}, at a concentration of 282 ppm Be. Carrier added to blank: 0.825 g.

Sample location, sample ID (Lat/long)	Grain size (µm)	Measured AMS ^{10}Be / ^{9}Be ratio (10^{-13})	Be carrier (g)	^{10}Be concentration (10^5 atom g^{-1})	Latitude (deg)	Longitude (deg)	Average production rate (atom g^{-1} y^{-1})	Denudation rate (10^{-3} mm y^{-1})	Apparent (ky) age
Iriri before Xingu (XIN13-01)	250–710	4.8 ± 0.09	0.828	2.42 ± 0.07	−3.823547	−52.677468	3.2 ± 0.2	8.49 ± 0.08	70.6
Xingu before Iriri (XIN13-07)	250–710	3.6 ± 0.06	0.822	1.78 ± 0.05	−4.038006	−52.594669	3.6 ± 0.2	13.2 ± 1.26	45.6
Xingu downstream Bacajaí (XIN13-20C)	250–710	4.2 ± 0.08	0.824	2.1 ± 0.06	−3.362553	−51.733718	3.5 ± 0.2	10.7 ± 1.0	55.9
Bacajaí (XIN13-26)	250–710	6.9 ± 0.13	0.818	3.45 ± 0.095	−3.588783	−51.763820	3.03 ± 0.2	6 ± 0.57	108.7
Wittmann et al. (2011) sample location								(Value recalculated)	
Xingu near São José do Xingu	125–250	–	–	2.55 ± 0.19	−10.763321	−53.099340	5.1 ± 0.3	13 ± 1.2	46.1
Xingu near São José do Xingu	250–500	–	–	2.32 ± 0.19	−10.763321	−53.099340	5.1 ± 0.3	14 ± 1.3	42.0
Xingu near São José do Xingu	250–500	–	–	2.25 ± 0.96	−10.763321	−53.099340	5.1 ± 0.3	15 ± 1.4	40.5

to lithophilic and rheophilic species like loricarid catfishes (Fig. 4). Furthermore, the clarity of the water may enhance the effects of substrate composition and coloration on the color patterns of fishes, especially lithophilic species. Thus, the concentration of suspended sediments and its variation due to changes in hydrology and vegetation cover may play an important role in fish evolution and ecology. Changes in riverbed complexity and fish diversity will be monitored during operation of Belo Monte dams. Digital elevation models (DEMs) such as SRTM (Farr et al., 2007) and ASTER GDEM (Tachikawa et al., 2011) and bathymetric surveys will provide information for morphometric analysis (Grohmann, 2004; Grohmann et al., 2007) of the Volta Grande region and correlation with niche segregation among fishes.

Figure 4. Diversity of sucker mouth armored catfishes (Loricariidae) in the Xingu River, with emphasis on lithophilous species. Clockwise from upper left: *Peckoltia vittata*, *Parancistrus nudiventris*, *Panaque armbrusteri*, *Scobinancistrus* sp., *Scobinancistrus aureatus*, *Squaliforma* sp., *Leporacanthicus heterodon*, *Ancistrusranunculus*. Center upper: *Baryancistrus xanthellus*. Center lower: *Spectracanthicus zuanoni*.

5.3 Core description and sampling

To date, two sediment cores (XC01-2 and XC05) have been opened for description and sub-sampling. Sediment core XC01-2 was collected in a floodplain lake under 1 m water depth, and it consists of ∼ 123 cm of sediments (Table 1). The lowermost portion (123–78 cm) presents medium to coarse sand with an overall fining upward pattern. Fine-grained muddy sediments with colors varying from dark gray (78–29 cm) to brown (29–0 cm) cover the sandy unit (Fig. 5). Three samples of wood sediments for radiocarbon dating and three samples for OSL dating were retrieved from the muddy and sandy beds, respectively. The XC05 sediment core was collected in the middle portion of the Xingu ria under a water depth of 13 m and comprises a sediment column of ∼ 470 cm (Table 1). This sediment core is characterized by dark gray to brown muds with rare fragments of plant material (Fig. 5).

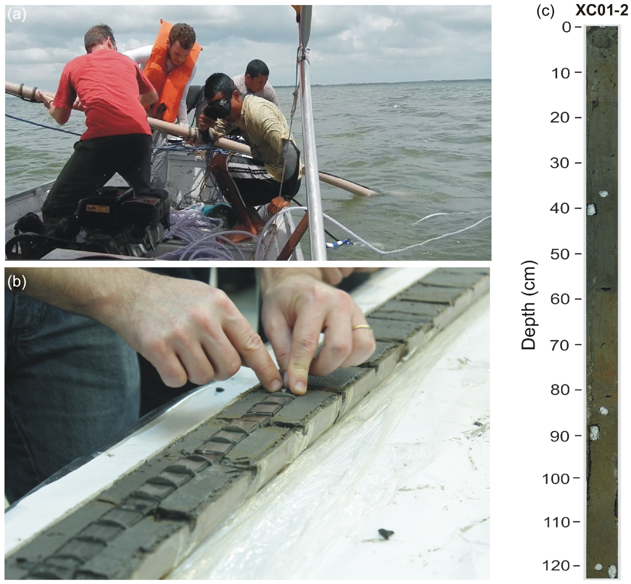

Figure 5. **(a)** Retrieving of the XC03 core during November of 2014. **(b)** Sampling of the XC05 core (470 cm) for magnetic analysis. This core is composed of homogenous organic muddy sediments. **(c)** Sediment column of the XC01-2 core, with a bottom sand layer covered by dark gray to brown muds.

Sediment samples for measurements of CH_4 concentration were collected at 10 cm intervals immediately (4–5 h) following coring, to avoid CH_4 oxidation. Samples for quartz OSL dating and for radiocarbon dating of particulate organic matter were collected at intervals of 30 to 40 cm. Samples for pollen/spore, diatoms, magnetic minerals, and organic and inorganic sediment geochemistry analyses were collected at 2 cm intervals.

5.4 OSL and ^{14}C dating

The samples at 120 and 84 cm depth from core XC01-2 were prepared for quartz OSL dating in the Luminescence and Gamma Spectrometry Laboratory of the Institute of Geosciences of the University of São Paulo. These samples represent the sand bed (bar top) underlying muddy sediments of the floodplain lake. Equivalent doses (De) were estimated using the single-aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2003) in multigrain aliquots (180–250 µm grain size). Equivalent doses were calculated using 24 aliquots per sample and the Central Age Model (Galbraith et al., 1999). Radiation dose rates were calculated through radionuclide concentrations measured using high-resolution gamma spectrometry. Samples at 120 and 84 cm presented sediment deposition ages of 6987 ± 513 years (De = 5.89 ± 0.20 Gy; dose rate = 0.843 ± 0.055 Gy ka^{-1}) and 4318 ± 278 years (De = 3.58 ± 0.10 Gy; dose rate = 0.829 ± 0.048 Gy ka^{-1}), respectively. Thus, sediment core XC01-2 records sediment deposition since the Middle Holocene, with the floodplain lake established approximately 4318 ± 278 years ago.

5.5 Magnetic analysis

Environmental magnetism techniques are used to investigate the formation, transportation, and depositional and post-depositional alterations of magnetic minerals in sediments (Thompson and Oldfield, 1986; Evans and Heller, 2003). Changes in the concentration, grain size and shape of magnetic minerals are related to climate through processes affecting sediment composition and texture, such as weathering conditions, vegetation type and erosion rates in the sediment source areas.

Magnetic susceptibility measurements of core XC05 were performed at the Paleomagnetic Laboratory of the Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo (IAG/USP). Paleomagnetic specimens from the XC05 sediment core were collected using cubic plastic boxes (8 cm^3) placed side-by-side continuously with orientation to the top–bottom, totaling 194 specimens (Fig. 5b). Low-field magnetic susceptibility of each specimen was measured using a Kappabridge MFK1-FA system (AGICO Ltd) with two different frequencies of 976 and 15 616 Hz in a 200 A m^{-1} field at room temperature (Dearing et al., 1996). Magnetic susceptibility values vary from $\sim 2.8 \times 10^{-8}$ to $\sim 1.8 \times 10^{-7}$ m^3 kg^{-1} (Fig. 6). Some strong variations (peaks) may indicate variations in sedimentation rate or different magnetic minerals present in the XC05 core. Additional magnetic analyses will be applied to determine the magnetic carriers and their nature.

5.6 CH_4 production and emission

The Xingu ria has lake-like sedimentary dynamics and thereby serves as an analogous setting for the future of Belo Monte's reservoirs. Many insights about future changes in GHG emissions can be obtained through the study of CH_4 and CO_2 dissolved in the water and within the sediments of the Xingu ria. To this end, we measured natural emissions of GHG and collected gas samples extracted from pore water of the XC05 core to evaluate the effect of sediment texture and composition on the production and flux of CH_4 and CO_2. CH_4 and CO_2 flux measurements from rivers were performed according to Sawakuchi et al. (2014) using simultaneously five floating chambers. At the same time, surface waters were collected to determine gas concentration in the water after headspace extraction. Dissolved gas concentration was calculated using Henry's law adjusted for temperature (Wiesenburg and Guinasso, 1979). Fluxes from soils were measured using static chambers and procedures similar to the used by Neu et al. (2011). Gas samples were analyzed on a Picarro Cavity Ring Down Spectroscopy Analyzer (model G2201-i). The CH_4 concentration in pore waters from the XC05 core ranged from 0.1 to 24.5 % (Fig. 6). The stable carbon

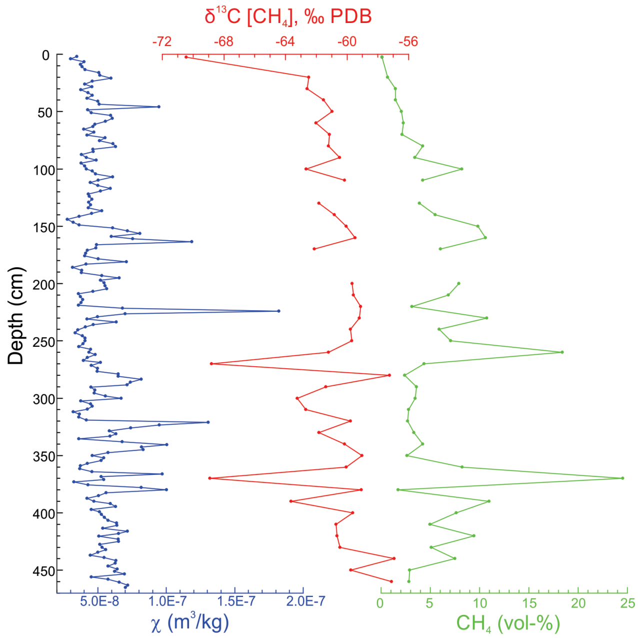

Figure 6. Low-field magnetic susceptibility by mass normalized of sediments and concentration CH_4 (vol-%) and stable carbon isotopes $\delta^{13}C$ $[CH_4]$ ‰ PDB in pore waters of XC05 sediment core. Data plotted as a function of depth.

isotopes ratio ($\delta^{13}C$) in CH_4 varied from −70.4 to −56.9, pointing to a biogenic origin. More positive values of $\delta^{13}C$ in CH_4 are related to higher magnetic susceptibility, suggesting a relationship between methane oxidation and concentration of magnetic minerals. Intervals with higher $\delta^{13}C$ in CH_4 could be related to oxygen-enriched pore waters, favoring the formation of authigenic iron oxides and increasing magnetic susceptibility. However, additional studies for characterization of magnetic mineral types are necessary to explain the relationship between CH_4 oxidation and magnetic susceptibility. Figure 6 shows the CH_4 and magnetic susceptibility data obtained for the XC05 core.

5.7 Palynology and diatom analysis

Analyses of pollen, spores (plants and algae), diatoms, sedimentary pigment degradation units (SPDU) and charred microparticles will be employed from the Xingu sediments as proxies for the identification of climatic forcing on forest dynamics versus human manipulation of the local vegetation in close interval sampling in the sediments. Diatom analysis in conjunction with SPDU will provide an indirect measurement of former lake levels, as well as determine possible episodes of marine water incursions into the ria system. Changes in river dynamics and vegetation will be studied through a proxy approach applied to the organic particles (charcoal, pollens, spores and diatoms) in sediment cores. Samples for palynological and diatom analysis were collected in intervals of 2 cm. Establishment of vegetation dynamics as influenced by global patterns of climatic change and local human manipulation of forest elements will also help to trace local surface processes, as they share a common temporal sequence. Lake levels, inferred from diatom and SPDU profiles, will allow for a better understanding of water depth variation in the lake system, and will provide means for a better interpretation of pollen and spore signals in lake sediments. In general, the combination of different biological proxies will permit the evaluation of human impact on the local Late Holocene landscape and the possible occurrence of cultural forests, which in turn may help explain the distribution pattern of *Terra Preta de Índio* sites in central Amazonia. Pollen analysis and associated biological indicators will result in a high-resolution paleocological record, which is lacking for the Xingu region. Preliminary palynological analyses of cores XC01-2 and XC05 indicate an abundant representation of arboreal taxa such as *Cecropia*, *Cedrela*, *Cordia*, Euphorbiaceae, *Genipa*, Fabaceae, Lecythidaceae, *Mauritia*, Melastomataceae, Moraceae, Myrtaceae and *Pouteria* and herbs belonging to the Cyperaceae and Poaceae families. Typical taxa of open vegetation are found in low percentages and concentration. Regarding diatoms, sediment cores XC01-2 and XC05 present well-preserved frustules with species variation along the core. Core XC01-2 presents at the base (122–98 cm) species of the genus *Aulacoseira* (*A. granulata*, *A. ambigua*, *A. granulata* var. *australiensis*), indicating a turbulent water environment. Diatoms are absent between 98 and 70 cm in depth, suggesting a dry period. Great variability of genera such as *Cyclotella*, *Discostella*, *Pinnularia*, *Encyonema*, *Staurosira*, *Aulacoseira* and *Eunotia* is observed towards the core top (68–0 cm). Core XC05 shows diatoms throughout the entire retrieved sediment column, but with little variation among genera, pointing to a more uniform slack water environment. Representatives of the genera *Surirella*, *Diploneis*, *Aulacoseira*, *Placoneis*, *Gomphonema*, *Encyonema* and *Eunotia* were observed throughout this core.

5.8 Geochemistry

A comprehensive suite of geochemical analyses will be applied to sediment cores XC01-2 (floodplain lake site) and XC05 (southern Xingu ria site) in order to infer patterns of environmental change for the Xingu region. Downcore variability in organic and inorganic sedimentary components are commonly paired with biological proxy information (e.g., from pollen, diatoms, benthic invertebrates, and fish fossils) in the study of evolving floodplain lake systems (McGlue et al., 2012; Moreira et al., 2013). Together, these data demonstrate how climate or human activities may influence water levels, hydrochemistry, marine connectivity, and ecological relationships. For cores XC01-2 and XC05, inorganic geochemistry will utilize carbonate coulometry and energy dispersive X-ray fluorescence (XRF) measurements collected at a 2 cm interval. Considering sedimentation rates expected for the coring sites, the 2 cm sampling interval is sufficient to capture transitions in depositional processes that may be responding to natural or human modification of the surrounding land surface in the decadal to millennial timescales. XRF provides both major and trace element sediment chemistry, which allows a robust mineralogical model to be constructed and potentially affords new insights into dynamic Holocene limnological processes. Organic geochemistry will focus on elemental analysis and stable isotopes of carbon and nitrogen, which will be used to deduce trends in primary productivity, organic matter preservation, and provenance. The synthetic multi-proxy approach we have adopted will greatly expand paleo-record development for the region, which may hold promise for predicting the response of this unique aquatic ecosystem to future disturbances (Gell and Reid, 2014).

6 Future activities

A workshop is planned for 2016 to integrate and discuss results of environmental proxies in core sediments, cosmogenic nuclides, thermochronology data, greenhouse gases, and geological correlations with fish diversity. In addition to its unique ecological-landscape character, the Volta Grande do Xingu is also the first clearwater river threatened by the new round of hydropower expansion in the Brazilian Amazon. Thus, lessons from the Volta Grande act as a reference for evaluation of hydropower projects planned for other analogous rivers like the Tapajós River. Environmental impacts of the Belo Monte dams on the Volta Grande were evaluated based on sedimentation data for short time intervals (a few years), considering the size and complexity of the ecological system. Understanding past changes in hydrology, sedimentation and vegetation in decadal to millennial timescales will support more reliable predictions of future ecological scenarios. The major challenge of the project that will be addressed in the workshop is the integration among studies dealing with different timescales, from the geological evolution of the Volta Grande and its role in fish diversity to modern and future influence of anthropogenic activities on river substrates and GHG emissions. To extend the age of environmental reconstructions, future drilling to obtain deep sediment cores in the Xingu ria system will be discussed. Researchers and students interested in the Xingu project are welcome to join the workshop.

Author contributions. H. O. Sawakuchi and D. J. Bertassoli performed greenhouse gas sampling and analyses. J. L. Antinao contributed to rock and sediment sampling for cosmogenic nuclides analyses and is performing analysis of ^{10}Be. M. Parra contributed to riverbed rock sampling and thermochronology analysis. L. M. Sousa and M. H. Sabaj Pérez contributed to fish collection and characterization of fish diversity and river substrate. P. E. Oliveira, R. A. Santos and V. B. Medeiros are contributing to palynology analysis and core description. G. A. Hartmann and J. F. Savian are contributing to magnetic analysis and ^{14}C dating. F. N. Pupim and C. H. Grohmann are contributing to geomorphological analysis and maps. F. N. Pupim and A. O. Sawakuchi are contributing to OSL dating. D. C. Bicudo and S. B. Faustino are contributing to diatom analysis. M. McGlue is contributing to geochemical analysis (XRF, C and N). A. O. Sawakuchi and G. A. Hartmann organized the coring collection and organized the writing of the manuscript, with contributions of all authors.

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Scientific Drilling
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Why deep drilling in the Colônia Basin (Brazil)?

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Abstract. The Colônia Deep Drilling Project held its first International Continental Scientific Drilling Program (ICDP) workshop in September 2014 at the University of São Paulo (Brazil). Twenty-seven experts from six countries discussed the feasibility and the expectations of a deep drilling in the structure of Colônia located at the southwestern margin of the city of São Paulo. After presenting the studies performed at the site during the last decades, participants focused on the objectives, priorities and detailed planning for a full deep-drilling proposal. An excursion to the site and new auger coring showed the importance of the Colônia site for studying the evolution of a tropical rainforest and to evaluate the interplay between the South American summer monsoon, the Intertropical Convergence Zone (ITCZ) and the southern Westerlies belt during the last 5 million years. In addition, deep drilling will eventually solve the still unresolved issue of the origin of the structure of Colônia as a result of meteorite impact or endogenous processes.

1 The Colônia site

In September 2014, an International Continental Scientific Drilling Program (ICDP) sponsored workshop was organized in São Paulo (Brazil), gathering a large group of scientists involved in the study of various aspects of the Colônia structure. This circular structure of 3.6 km diameter is located in the coastal mountain range of Brazil, in the Atlantic Forest domain, at the periphery of the city of São Paulo (23°52″ S 46°42′20″ W, 900 m a.s.l.; Fig. 1). The structure has been known, and its origin debated, since the early 1960s. The first geophysical investigations suggested that the basin could be as deep as 300 to 450 m, and results of several complementary geophysical methods have since been used to constrain the geometry of the crater-like structure and to provide a preliminary stratigraphic framework. The structure was formed in crystalline basement rocks, mostly granitic gneiss, some schists and quartzites of Neoproterozoic age (600–700 Ma; Hasui et al., 1975). Their presence provides the only available (maximum) age constraint for the formation of this structure. The near-circular rim is formed by a prominent annular ring of hills rising up to 125 m above the inner depression of Precambrian basement rocks. The basin stratigraphy essentially comprises organic-rich and fine-grained sediments (silt and clay), with intercalations of sandy mud. The presence of Precambrian rock fragments in a matrix-supported conglomerate found at ∼350 m depth points towards a fanglomeratic deposit derived from the highest parts of the outer rim and is most probably related to the initial infilling of the depression (Riccomini et al., 2011).

Riccomini et al. (2011) discussed various alternative processes to explain the origin of the Colônia structure. Impact cratering has remained the preferred agent (e.g., Velazquez et al., 2014) despite a lack of unambiguous evidence. This impact hypothesis is supported by the overall geometry of the structure because the geology does not provide any other

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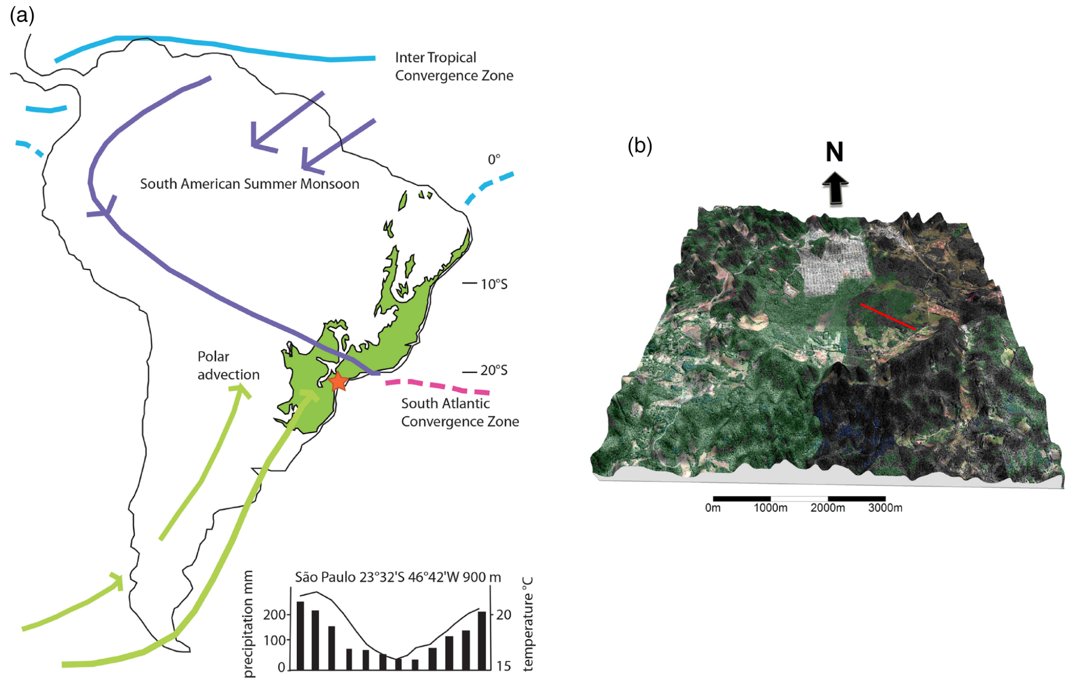

Figure 1. **(a)** Map of South America. The green area illustrates the present extent of the Atlantic rainforest and the red star indicates the location of Colônia. The site is located in a key position between the austral summer (north of Colônia) and winter (south of Colônia) rainfall pattern and atmospheric circulation. The northern circulation is dominant today with the activity of the South American summer monsoon (purple) and Intertropical Convergence Zone (ITCZ) seasonal shifts (light blue plain and dotted lines showing austral winter and summer positions, respectively). **(b)** 3-D view of the Colônia structure combining an Ikonos satellite image and a digital elevation model with a 6.5x vertical exaggeration. The red line indicates the present extent of the bog.

plausible explanation for the formation of such a distinct circular shape by endogenic or exogenic processes. Riccomini et al. (2011) also noted that the current depth-to-diameter ratio is different from similarly sized and comparatively deeper known impact structures (e.g., Brent Crater, Ontario, attains a depth in the inner part of the basin of 1000 m). This was interpreted as indicating that the crater could have been substantially eroded since its formation. No datable material related to basin formation has been found at Colônia so far. Consequently, comprehensive drilling of the structure is required to provide a means of constraining its origin and to have a chance of obtaining datable material (Reimold et al., 2014).

The Colônia Basin is a unique site for regional as well as global paleoclimatic investigations (Fig. 1a), as it has remained a closed basin system ever since its formation. Based on geophysical data by Riccomini et al. (2011), the continuous sedimentary infill could provide an extended and unique paleoenvironmental record for the Southern Hemisphere tropics and, in particular, for Atlantic tropical rainforest evolution. Much of what is currently known about the Colônia infill comes from sedimentological and palynological studies of the upper 8 m, which provided a record of 130 ka (Fig. 2; Riccomini et al., 1991; Ledru et al., 2005, 2009). In 2009, Ledru et al. estimated that the complete depositional record could span at least 1.5 to 2.5 Ma.

2 Scientific issues

The Colônia Basin is located on the southernmost influence of the South American subtropical monsoon (SASM) and the northernmost limit of polar air advections (Fig. 1a). Previous paleoclimatic studies have shown that these climatic limits have shifted during the last 130 ka. For instance, speleothem records from relatively close to the Colônia site show that orbital cycles, and more particularly the precession signal, control the distribution of regional precipitation (Cruz et al., 2005). Pollen analysis reveals that this precession signal has also paced phases of expansion and regression of the Atlantic rainforest (Ledru et al., 2009; Fig. 2). Consequently, Colônia offers an ideal site to test hypotheses of paleoecological responses to climate change; the impact of orbital cycles on tropical moisture regimes and water resources; the speciation of living organisms ranging from plants to ostracods; biodiversity processes; links of this area with the Amazon rainforest during several glacial–interglacial cycles; and to provide information on the Tertiary–Quaternary boundary in the Southern Hemisphere. Thus, drilling Colônia will allow us to test hypotheses relating to vegetation community compo-

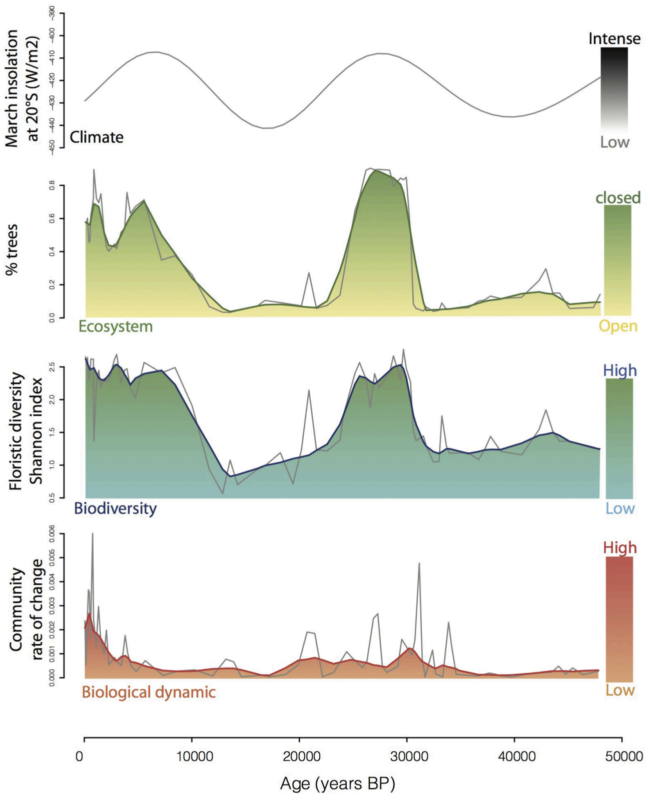

Figure 2. Synthetic diagram showing, from top to bottom, the insolation at 20° S (from Berger and Loutre, 1991), the arboreal pollen (AP) frequencies, the floristic diversity index, and the community rate of change in the pollen record of Colônia during the last 50 ka. The figure illustrates the relation between the forest expansion/regression phases and the pace of the precession signal (modified by L. Bremond and C. Favier in Prospectives Ecologie Tropicale 2014).

sition, ecosystem resilience, niche effectivity, and migratory response. Additionally, for the first time, the limits of deep microbial life can be investigated in a deep drilling project at this southern latitude.

Several open questions regarding the Colônia structure can be answered only through deep drilling.

1. What is the origin of this enigmatic basin structure?

   Rock samples retrieved from the drilling will be investigated for the occurrence of unambiguous shock (impact) metamorphic features, such as shatter cones and planar deformation features. Any possibly observed shatter cones will be investigated visually. Other microscopic shock features (e.g., planar deformation features – PDF) will be investigated by optical microscopy and, if required, by electron microscopic techniques. Should the structure be of impact origin, shock deformed minerals may occur in impact breccias, possibly even including impact melt rock. The latter would provide the best means for dating of the basin-forming event. Should impact melt rock be drilled, it may also contain a trace of the extraterrestrial projectile that might be amenable for identification of the projectile type. Pseudotachylitic breccia in the sub-basin basement could also be related to the basin-forming event and may be datable. Hydrothermal activity might have affected a crater-floor section and could become an important subject of chemical and petrographic investigation.

2. What is the age of the structure?

   Drilling deep will allow searching for melt fragments where an absolute date may be established by radiometric dating using the $^{40}Ar/^{39}Ar$ method. Paleomagnetism will be performed continuously on the core to establish the magnetic stratigraphy, and combined optically stimulated luminescence (OSL) and radiocarbon datings will constrain the age model on the last four glacial/interglacial cycles. Additionally, statistical analyses will be used to compare changes in geo- and bio-indicators with neighboring speleothem and marine records as well as to identify hiatuses within the sediment deposit.

3. How did the tropical Atlantic rainforest respond to several successive glacial–interglacial and orbital cycles?

   While the last glacial maximum is the expression of the eccentricity element of the orbital cycle, paleoclimatic reconstructions from speleothems (116 ka) suggest that the precessional element of the orbital cycle was rather the main driver for changes in precipitation regimes in eastern South America (Cruz et al., 2005). However, spectral analysis on arboreal pollen frequencies on three long Quaternary records of vegetation in the tropics (Fuquene, 1 Ma, Bogota et al., 2011; Lynch Crater, 230 ka, Kershaw et al., 2007; Colônia, 130 ka, Ledru et al., 2009) revealed the imprint of the three orbital cycles, eccentricity, obliquity and precession, in the past distribution and composition of the rainforest. This new field of research still needs more long record studies.

4. What are the evolutional processes of tropical species?

   While most Amazon and Atlantic forest species started to diverge during the Tertiary, a large number of new species emerged during the Quaternary. Recently, phylogeographers working in the Atlantic rainforest showed that diversification and molecular timescales are not always correlated with successive glacial maxima (Ribas et al., 2012). Long records will contribute to characterizing the nature of the link between divergence and changes in the Earth's total thermal energy.

5. How did changes in the equator–pole temperature gradient impact on the distribution of the Atlantic rainforest?

The long pollen records of Fuquene in Colombia (Bogota et al., 2011) and Lynch Crater in Australia (Kershaw et al., 2007) show that the variability of the temperature gradient between low and high latitudes defines the strength and position of the South American summer monsoon on the continent and is paced by the obliquity signal at ∼ 40 ka. The high-resolution record of Potrok Aike, obtained from a previous ICDP-sponsored lake drilling project (Zolitschka et al., 2013), will be used to define the shifts of the wind belts and their impact on the SASM amplitude and intensity at the latitude of Colônia during the late glacial as well as to characterize the link between low- and high-latitude circulation.

6. What is the link to Amazon rainforest and to Andean forest?

   A possible link between the Amazon and Atlantic forests was observed in northeastern Brazil during the late glacial and between the Andean and Atlantic forests in southeastern Brazil during the last glacial (Ledru et al., 2009). How often were these links repeated during the Cenozoic?

7. What is the nature and extension of the subsurface microbial biosphere in this environment?

   Peat bogs are significant contributors to the global carbon cycle, acting as large repositories of atmospheric carbon and containing over one-third of the organic carbon in global soils. Emissions of methane and CO_2 greenhouse gases occur primarily by two processes: methanogenesis and methane oxidation that are closely associated with microbial activity (Ariztegui et al., 2015). Determining their activity in both the peat bog and the older lacustrine sediments will provide unique information about microbial activity in contrasting environmental conditions (glacial–interglacial) and their record in the sediments.

3 Outcomes of the São Paulo workshop on Colônia deep drilling

Twenty-seven scientists from six countries (Australia, Brazil, France, Germany, Switzerland, and the USA) participated in a workshop in São Paulo, Brazil, from 26 to 29 September 2014, to discuss scientific priorities and logistical requirements for accomplishing a deep drilling project at Colônia. The workshop was held at the Geosciences Institute of the University of São Paulo (USP). This location allowed students and faculty of the USP to actively participate in the workshop and closely interact with the science team.

Several invited speakers introduced the aspects that constitute the backbone of the Colônia project, including presentations on

1. a comparison of the Colônia structure with similarly sized impact structures in South America and elsewhere;
2. relevant Quaternary geological and paleoecological research;
3. review of the late Quaternary climatic controls based on stable isotope records;
4. the paleoecological potential of Colônia sediments and plausible links to planned projects on tropical biodiversity processes in the Atlantic rainforest;
5. methods and problems related to age modeling of Quaternary sediments;
6. investigating the subsurface biosphere in peat bog and lacustrine sediments; and
7. technical issues of deep drilling.

Additionally, several speakers presented results of previous drilling projects with emphasis on ICDP procedures and projects (F. Anselmetti, Switzerland; U. Harms, Germany; J. Overpeck, USA).

One full day was spent visiting the Colônia site located in the municipality of São Paulo some 42 km south of the city center. The group could familiarize itself with the logistical facilities offered by the relative proximity to the city, with accessible roads right into the basin and a track leading towards the center of the shallow bog. Using a Russian corer, a 14 m long sediment record was retrieved from the bog during this excursion (Fig. 3). This new core will provide datable material to clarify existing issues concerning the currently available age model. Furthermore, this core has shown the presence of laminated lake sediments below the topmost peat (Fig. 4).

A number of new aspects arose during the workshop, including the following.

- Results of reconnaissance seismic-reflection surveys suggest that the basin of the Colônia structure contains a thicker sedimentary sequence than previously thought. Further seismic investigations are needed to cover the entire structure, including the previously non-analyzed centralmost section, and to better constrain the best drilling location (Fig. 5).
- Sediment cores collected in 1989 were 7 and 8 m long, showing the presence of a thick and compacted peat (Riccomini et al., 2005). However, the lacustrine deposits in the new 14 m long core retrieved during the workshop open up new research perspectives.
- Preliminary luminescence data obtained at the Luminescence and Gamma Spectrometry Laboratory of the University of Sao Paulo (LEGAL-USP) during the

Figure 3. The drilling of core CO 14-1 performed during the excursion to the structure of Colônia. Photo credit: Marie-Pierre Ledru.

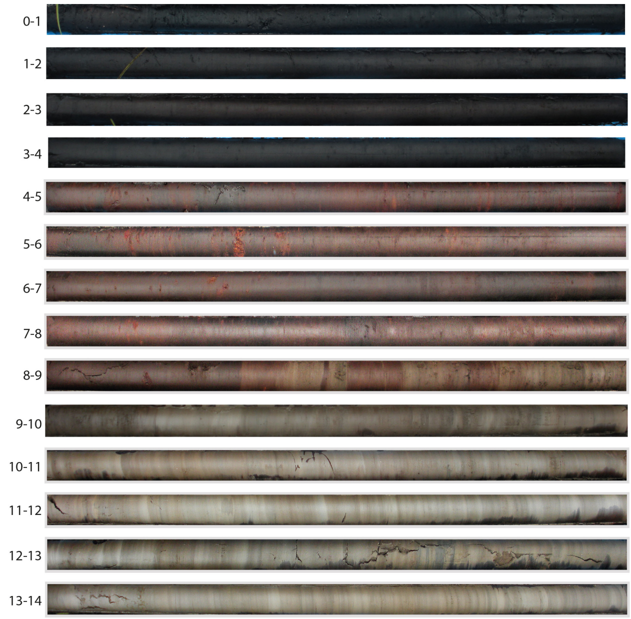

Figure 4. Sediments of the 14 sections of core CO 14-1 showing grey lacustrine deposits below 9 m depth, a transition between peat and lacustrine deposits between 9 and 8 m, and peat in the upper section.

night after coring showed quartz and potassium-feldspar grains suitable for optically stimulated luminescence (OSL) dating. Aliquots of potassium-feldspar grains indicated good infrared (IR) stimulated luminescence and post-IR signals able to recover a radiation equivalent dose up to at least 600 Gy. Aliquots of quartz grains presented high blue-stimulated luminescence and isothermal thermoluminescence (ITL) signals suitable for measurement of doses up to 150 and 500 Gy, respectively. The luminescence signals tested would be suitable for dating of sediments back to at least 400 ka, considering radiation dose rates of 1.2 and 1.7 Gy ka^{-1}, respectively measured for quartz and potassium feldspar. Other luminescence signals such as thermal transfer OSL and violet stimulated luminescence (VSL) can be tested as alternatives to extend the age range, possibly beyond the Quaternary.

– Paleomagnetic tests performed on a short core collected in 2010 had already provided the presence of a good magnetic signal, which will make magnetostratigraphy an additional dating tool for the part of the record older than the Brunhes–Matuyama boundary (0.78 Ma).

– Qualitative and semi-quantitative determinations of the mineral assemblage will complete the lithological description of the Colônia sedimentary sequence. The crystallinity index is expected to increase in the lacustrine sediment succession, with respect to mineralogy in the present bog. Detrital mineral input allows inferring of the degree of weathering at the time of deposition, whereas authigenic minerals are controlled by the biogeochemical cyclicity within the paleo-lake. Additionally, detailed mineralogical investigations might provide information on whether cryptotephras are preserved in the Colônia sequence and can be used as another dating tool.

– Stable isotopes on organic matter (nitrogen and organic carbon isotope composition) and on bulk carbonates (carbon and oxygen isotopes) will be used as potential proxies for nutrient cycling, carbon sources, and climatic change.

– The lacustrine sections will be investigated for biological remains such as diatoms and ostracods allowing a quantitative estimation of lake level changes and associated variations in water chemistry.

4 Opportunities and tasks

The workshop participants concluded that additional pilot data must be acquired before presenting a full proposal in January 2016. In the course of the coming months, the newly retrieved core will be extensively analyzed, including non-destructive X-ray diffraction (XRD) analysis of bulk powder samples; stable isotope analysis; paleomagnetism; OSL and radiocarbon dating; and ostracod and diatom analysis. An improvement of the presently available geophysical data is critical. New gravimetric data have already been ac-

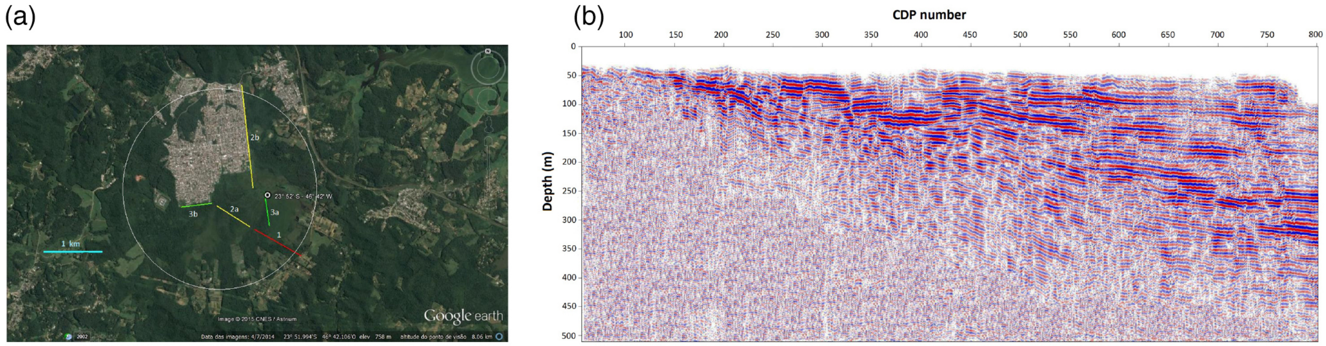

Figure 5. **(a)** Satellite view of the structure of Colônia showing the location of the 2010 seismic section (red line) and the sections planned for 2015. **(b)** Results of the 2010 seismic section along the Colônia structure (common depth point (CDP) trace interval = 1 m). The bright red and blue colours show the uninterpreted sedimentary infill of the basin(from Riccomini et al., 2011).

quired and an additional seismic data acquisition campaign is planned for the dry season of 2015 (May–July; Fig. 5a).

A second workshop of PIs and scientific team members was called for February 2015 at the University of Campinas, in the city of Campinas (Brazil). The main objective for this meeting was the discussion of progress and organization to acquire additional seismic profiles covering the central part of the structure, as well as debate of the preliminary results of the new core. Presentations by and about tender drilling companies allowed assessing of the budget requirements for drilling operations to be comprehensive but economic.

Participants in the workshop

Flavio Anselmetti, Daniel Ariztegui, Laurent Augustin, Laurent Bremond, Manoel Cardoso, Ana Carolina Carnaval, Marlei Chamani, Cristiano Chiessi, Alvaro Crósta, Francisco Cruz, Paulo De Oliveira, Thomas Fairchild, Charly Favier, José Antonio Ferrari, Maria Judite Garcia, Uli Harms, Fred Jourdan, Marie-Pierre Ledru, Vanda Medeiros, Cristina Miyaki, Grace Oliveira, Jonathan Overpeck, Vania Pivello, Renato Prado, Fabiano Pupim, Fresia Ricardi-Branco, Rudney de Almeida Santos, Wolf Uwe Reimold, Claudio Riccomini, Patricia Roeser, Lucy Sant'Anna, André Sawakuchi, Giancarlo Scardia, Tim Shanahan, Nicolás Strikis, Ricardo Trindade, Marcos Vasconcelos, Ilana Wainer, Suely Yoshinaga Pereira, and numerous other colleagues and students that listened to the presentations.

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Scientific Drilling
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Trans-Amazon Drilling Project (TADP): origins and evolution of the forests, climate, and hydrology of the South American tropics

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Abstract. This article presents the scientific rationale for an ambitious ICDP drilling project to continuously sample Late Cretaceous to modern sediment in four different sedimentary basins that transect the equatorial Amazon of Brazil, from the Andean foreland to the Atlantic Ocean. The goals of this project are to document the evolution of plant biodiversity in the Amazon forests and to relate biotic diversification to changes in the physical environment, including climate, tectonism, and the surface landscape. These goals require long sedimentary records from each of the major sedimentary basins across the heart of the Brazilian Amazon, which can only be obtained by drilling because of the scarcity of Cenozoic outcrops. The proposed drilling will provide the first long, nearly continuous regional records of the Cenozoic history of the forests, their plant diversity, and the associated changes in climate and environment. It also will address fundamental questions about landscape evolution, including the history of Andean uplift and erosion as recorded in Andean foreland basins and the development of west-to-east hydrologic continuity between the Andes, the Amazon lowlands, and the equatorial Atlantic. Because many modern rivers of the Amazon basin flow along the major axes of the old sedimentary basins, we plan to locate drill sites on the margin of large rivers and to access the targeted drill sites by navigation along these rivers.

1 Introduction

The origin of the great biodiversity observed in tropical South America has spurred debate for well over a hundred years (Darwin, 1859; Agassiz and Agassiz, 1868; Wallace, 1878) and remains one of the foundational problems in modern science. Wallace (1878) suggested that low tropical extinction rates, resulting from a relatively equitable and stable tropical climate, enabled the progressive accumulation of species throughout the Cenozoic, a hypothesis that has been termed the "museum" model. In contrast, the "cradle" model (Stebbins, 1974) posits that most tropical diversity arose from episodic pulses of speciation associated with climatic and geological drivers (Richardson et al., 2001). Some propose that the majority of present-day species originated prior to the Pleistocene (Hoorn et al., 2010) and that species origination rates were shaped primarily by geological agents of vicariance, such as Andean uplift, tectonic arches, marine incursions, fluvial barriers, and the expansion of megawetlands. Others argue for significant Quaternary diversification, influenced by the temporal and spatial dynamism of regional climate (Rull, 2011). These different interpretations of the patterns and drivers of tropical biodiversity can best be resolved by recovering the entire Cenozoic record of plant diversity in the Amazon region itself and by placing these biotic data into a well-resolved geologic, climatic, phylogenetic, and biogeographic framework.

We propose an ambitious ICDP drilling project that will continuously sample Upper Cretaceous to modern sediment to 1–2 km depth at five sites in four different ancient sedimentary basins that transect the equatorial Amazon region of Brazil, from the Andean foreland to the Atlantic Ocean margin (Fig. 1). The overarching goals of this project are (1) to document the assembly of Amazon plant diversity across the entire basin throughout the entire history of the angiosperm-dominated megathermal forests, and (2) to determine how the evolution of the physical environment, including climate, tectonism, and landscape change, has shaped the generation and distribution of neotropical plant diversity and the origins of its species and higher-level taxa. These goals require long sedimentary records distributed across the continent, which, in most of the Amazon region, can only be obtained by drilling.

The Cenozoic geology of the westernmost (proximal Andean) and easternmost (offshore Foz do Amazonas basin) parts of the Amazon region is better known than that of the central Brazilian Amazon, where we propose to drill. In the far western Peruvian, Ecuadorean, and Colombian Amazon, ongoing uplift of Andean foreland basin sequences provides outcrops of Cenozoic sediments that are relatively easily accessed. Yet even here, complete and continuous sections are non-existent. Beyond the eastern limit of the Amazon region, on the Ceará Rise far offshore of the mouth of the Amazon, drilling during ODP Leg 154 recovered long sequences of sediment with some Amazonian provenance (Dobson et al., 2001; Harris and Mix, 2002). Even longer stratigraphic records were recovered in industry exploration wells on the Amazon slope and shelf, which were dated using marine microfossils. But these sections are poor records of continental history, because they are distal to the Amazon basin itself and because continental indicators of climate and biotic history are greatly diluted by marine influences. In the heart of the central Brazilian Amazon, Cenozoic outcrops are scarce, vegetation-covered, and deeply weathered – the critical sedimentary sequences are only available in the subsurface. And, despite extensive hydrocarbon exploration undertaken in this region, including many deep drill cores and thousands of kilometers of seismic lines, little is known about the non-petroleum-bearing shallow (Cenozoic age) part of the sedimentary record, which holds key information about the evolution of the modern rainforest and the establishment of the Amazon river drainage system. Most of the samples that are still available are decades old, composed only of cuttings, undated, in poor condition, and sometimes contaminated, and also relatively difficult to access even by Brazilian scientists. Thus, collecting continuous, fresh drill cores from the central Amazon region is critical.

In March 2015, we held a 3-day ICDP-sponsored workshop at the Instituto Nacional de Pesquisas da Amazônia in Manaus, Brazil, to discuss the scientific framework for the TADP, to identify and begin to resolve technical and logistical issues, and to further develop the international team needed for carrying out the drilling and associated science. Thirty scientists from eight nations in the Americas and Europe attended. The first day included overview presentations on the history of the Amazon forest and its biodiversity and on the geologic history of the Amazon and Andes, as well as presentations on recent research results on more specific topics. The second day was devoted to small group discussions of methodological and logistical issues, followed by discus-

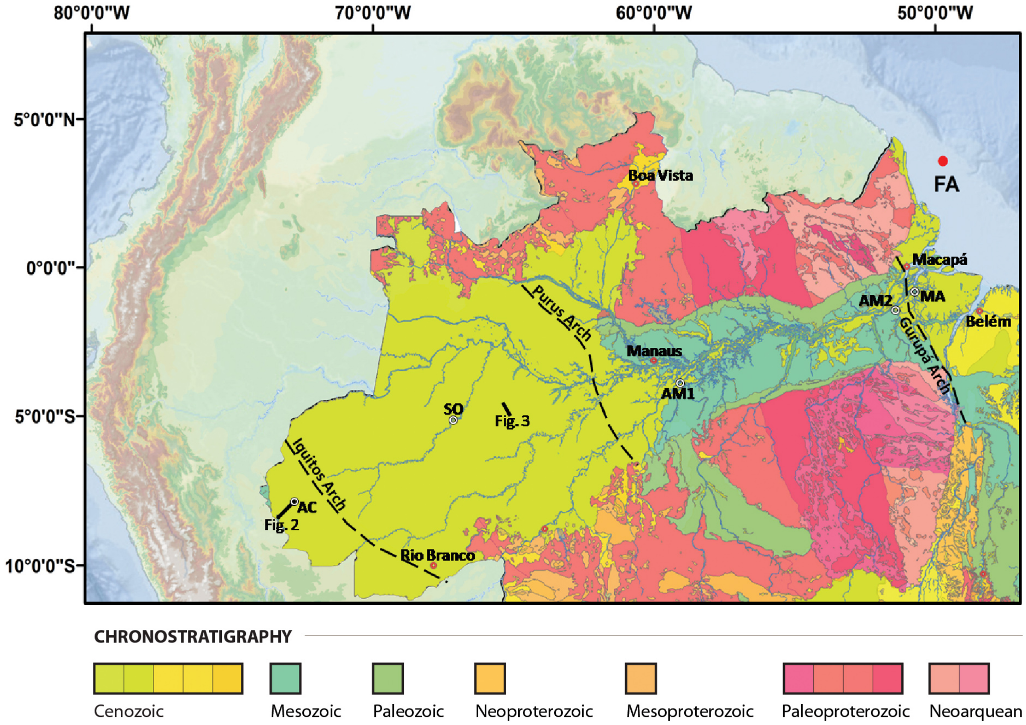

Figure 1. Geologic map of the Amazon region. Note that the newly revised geologic map of Brazil shows that the sedimentary cover of the Amazon basin is Cenozoic (not Cretaceous as shown here; see Caputo, 2011). Also shown are the locations of seismic lines in Figs. 2 and 3 and proposed drill sites. Drill site locations are shown for the Acre (AC), Solimões (SO), Amazon (AM), and Marajó (MA) basins. Each of these basins is separated from the adjoining basin by structural arches, as shown on the figure.

sions on how to develop the drilling plans and effectively interface with ICDP, IODP, various Brazilian organizations, and other related international efforts. The final day featured a field trip led by Edgardo Latrubesse, visiting the flooded Igapó forests and white sand beaches along the Rio Negro, as well as the "Meeting of the Waters" at the confluence of the black-water Rio Negro and the white-water Rio Solimões.

2 The geographic framework of the Brazilian Amazon

South America is a continent, more so than any other, whose land surface is dominated by large rivers. Many of these modern rivers flow along the major axes of old sedimentary basins. The Brazilian Amazon region itself (Fig. 1) is largely comprised of a series of east–west trending basins that began accumulating sediments in the Paleozoic, overlying and bounded north and south by Precambrian continental basement rocks. From west to east these basins are the Acre, Solimões, Amazon, Marajó, and Foz do Amazonas (which includes the Amazon deep-sea fan); all of these basins have several kilometers of sediment fill (Cunha, 2007; Cunha et al., 2007; Figueiredo et al., 2007; Filho et al., 2007, Zalán and Matsuda, 2007). This geographic coincidence is significant for the proposed drilling, because it means that the modern Amazon river provides easy access to several different sites where, by drilling along the river margins, we can access nearly the entire Cenozoic history of the Amazon forest and its climate. Each of the Amazon sedimentary basins is separated from its neighbor by structural highs that displace basement rocks, have been reactivated many times in the Phanerozoic, and, in some cases, may remain active to the present day. From west to east these structural features are the Iquitos Arch, Purus Arch, Gurupá Arch, and an un-named structural high Amazon basin. Some of these features have previously been posited as topographic highs that played a role in the development of Amazon transcontinental drainage (Figueiredo et al., 2009) or the origins of Amazon biodiversity (Patton et al., 2000; Ribas et al., 2011).

3 The temporal development of the Amazon basin and its forests

In the Cretaceous, the South American continent occupied nearly the same latitude as today, but its tropical forests were dominated by gymnosperms and ferns and hence were completely different than modern forests (Morley, 2000; Graham, 2011; Jaramillo, 2012). The rise of angiosperms in the Early Cretaceous initiated major changes in the structure, function, and composition of the forest, changes that may have been influenced by the nearby Chicxulub impact event at the Cretaceous–Tertiary boundary. That event and the ensuing cascade of environmental responses brought about extinction of an estimated 48–70 % of the neotropical terrestrial plant species (de la Parra, 2009). The subsequent expansion of angiosperm megathermal forests has been linked to greenhouse climates (Morley, 2000; Fine and Ree, 2006), and studies from northern South America suggest that species diversity of forest plants increased in the early Cenozoic under warm conditions (Jaramillo et al., 2006), with the development of the neotropical rainforest at the onset of the Eocene (Morley, 2000). Palynofloral data from multiple sections in Colombia and Venezuela that span the Paleocene through Early Miocene (65 to 20 Ma) suggest maximum diversity at the Paleocene–Eocene Thermal Maximum (PETM) as a result of rapid plant diversification and biogeographic mixing (Jaramillo et al., 2006, 2010), followed by a subsequent decline, a pattern that mirrors global temperature reconstructions (Jaramillo et al., 2006). At least on the face of it, given the scant data, it appears that the early–mid-Cenozoic climatic "optimum" was an evolutionary "optimum", inviting the suggestion that rainforest plant taxa may survive and thrive in future global warming scenarios (Willis et al., 2010; Dick et al., 2013). Yet all of these studies of palynofloral diversity through time were undertaken outside the margins of the modern Amazon basin itself. Furthermore, no Paleogene sediments have been recovered and described from the Brazilian Amazon, and the published data from Neogene sequences from exploration wells and outcrops are largely from western Amazonia (Hoorn, 1993; Silva-Caminha et al., 2010). Thus, our knowledge of the history of the forests and forest diversity in the core of the Amazon Basin, and the associated climate history, is almost nonexistent. Recovering, dating, and analyzing Paleogene sediments from the drill cores for the first time is a major objective of this project.

A fundamental premise of much previous research on the history of South American tropical forests is that Andean surface uplift played a major role in the origin and distribution of neotropical biodiversity (Hoorn et al., 2010). Andean uplift sundered populations east and west, promoting their biological differentiation; it created new high-elevation habitats; it altered precipitation patterns and amounts; and it provided nutrients to the adjacent lowland rivers and forests.

The Andes developed along a Cenozoic convergent margin, where the oceanic Nazca plate subducts beneath South America. The Andes of Ecuador, Peru, and Bolivia consist of two parallel ranges: the Western Cordillera (WC) magmatic arc and the Eastern Cordillera (EC) fold-thrust belt. The timing of surface uplift and its spatial variation remain very poorly known, particularly in the case of the WC. Recent investigations in southern Peru suggest that modern WC elevations were attained about $\sim$19–16 Ma (Saylor and Horton, 2014). EC deformation and exhumation began in the Eocene with the so-called Incaic Orogeny (Megard, 1978; McQuarrie, 2002; Elger et al., 2005; Gillis et al., 2006). In contrast, in the northern Bolivian Altiplano, which lies between the WC and EC, Garzione et al. (2006) and Ghosh et al. (2006) concluded that surface uplift was rapid and occurred between $\sim$10 and 6 Ma. But their clumped isotopic paleoaltimetry estimates have been challenged (Ehlers and Poulsen, 2009; Poulsen et al., 2010; Insel et al., 2010; Garreaud et al., 2010; Barnes et al., 2008. In general, the emerging data suggest that the timing, rates, and mechanisms of uplift are not spatially uniform (Saylor and Horton, 2014). One of the best ways to constrain Andean uplift and erosion history and to disentangle the influences of climate and topography in affecting Andean isotopic records will be to determine the provenance and paleoclimate history of the ever-lowland sediments in drill cores recovered from the proposed drill site in the Acre foreland basin.

Much of western Amazonia was composed of actively subsiding foreland basins from the early Cenozoic to the present and, throughout this time, received sediments eroded from the Andes. In the early Cenozoic, the Amazon basin may have drained westward, then northward, while only the eastern third of the craton drained toward the Atlantic. At some later time, with estimates ranging widely between Miocene and Pleistocene, the Amazon system became a transcontinental fluvial basin (Hoorn et al., 2010; Latrubesse et al., 2010), and Andean sediments first reached the Atlantic basin.

Prior to establishment of trans-Amazon drainage, by some accounts, the Purus Arch (Fig. 1) formed the western limit of proto-Amazon drainage, possibly as late as the Pleistocene (Vega et al., 2006; Mapes, 2009). A counter point of view is that the Purus Arch was tectonically inactive during all of the Cenozoic and played no role as a drainage divide. Instead, it may have been the Gurupá Arch (Fig. 1), having undergone more than 5 km of total uplift since the opening of the Atlantic (Caputo, 2011), which was the key hydrologic barrier to eastward flow of the early Amazon. Yet the role of the Gurupá Arch in Amazon hydrology and biogeography has never been discussed in the literature.

During the Miocene, sedimentary sequences of the Pebas Formation in Peru or the equivalent Solimões Formation in Brazil reached a maximum thickness of 1100 m in the Acre Basin. However, interpretations of the age and depositional environment of these sediments are varied and controversial. Wesselingh (2006) argued for the existence of a long-lived (15 Ma) freshwater mega-lake or mega-wetland bisecting western Amazonia during the entire Early and Middle Miocene. Several studies from the early 1990s (Nutall, 1990; Hoorn, 1993) suggested that recurrent marine transgressions into the Amazon basin occurred during global sea-level high stands of the Miocene, and Räsänen et al. (1995) proposed that these extended all the way to southern Peru in the Late Miocene. In more recent literature, marine incursions or tidal influences of variable timing and spatial extent have been posited in multiple sedimentary models for Amazonia (e.g., Hovikoski et al., 2010; Hoorn et al., 2010; Boonstra et al., 2015). Yet the sedimentary structures and trace fossils proposed as marine are not uniquely associated with tidal systems (e.g., Westaway, 2006; Latrubesse et al., 2010). Constraining the nature and timing of the Amazon sedimentary environment with new drill cores across the basin is important, because many of these inadequately constrained aspects of the geological evolution of the Andes and Amazon have been invoked in biogeographic and phylogeographic models as barriers to gene flow and drivers of species diversification.

Controversy also surrounds the role of climate in driving neotropical speciation. Some argue that the majority of present-day species originated prior to the Pleistocene (Hoorn et al., 2010) and that species origination rates were largely independent of climate, thus shaped primarily by geological agents of vicariance, including uplift, marine incursions, mega-wetlands, riverine barriers, and arches. For example, Ribas et al. (2011) documented phylogenetic patterns in the flightless birds, the trumpeters (Aves *Psophia*), and demonstrated that their evolutionary history follows that of major lowland Amazon river drainages, suggesting a fundamental role for fluvial evolution, not climate variability, in bird diversification over the last 3 Ma. In contrast, other workers argue that species origins in the Amazon were the direct result of climate variability or at least that climate played a significant role (Rull, 2011). An early model of climate-influenced speciation is the refugia hypothesis (Haffer, 1969), which posits that during Pleistocene dry periods, the Amazon forest contracted into refugia and that populations isolated in these refugia underwent accelerated rates of diversification. Although most data suggest that the refugia hypothesis may not be correct in its original definition (Rull, 2011), this does not negate the possibility of considerable diversification during the Quaternary associated with climate-induced vegetation fragmentation and expansion (e.g., Cheng et al., 2013). These (and many other) different interpretations of the rates and drivers of tropical biodiversity can only begin to be resolved by recovering the entire Cenozoic record of plant diversity in the Amazon region itself and placing the biotic data into a well-resolved geologic, climatic, phylogenetic, and biogeographic framework.

4 Major questions to be addressed by drilling

1. What is the history of plant diversity across the Amazon basin? Is the Amazon a "museum", steadily accumulating diversity through time? Or does diversity covary with global temperature, perhaps as a result of areal expansion of the tropics? How does diversity respond to specific environmental drivers, such as Andean uplift? Are there any clear extinction events throughout the Amazon forest? What is the sequence of turnover of dominant plant families and genera across the basin? When did Andean-centered plant taxa expand across the basin? What was the nature of biotic change in the Amazon region across the Cretaceous–Paleogene boundary (e.g., de la Parra, 2009)? Contemporary α-diversity of trees is highest in western Amazonia, where precipitation is higher and soils are more fertile than farther east (ter Steege and RAINFOR, 2010). Did this west-to-east gradient persist throughout the Cenozoic? Is climate and diversity in some parts of the Amazon (for example, in the presently wetter western Amazon) more stable through time than in other regions? The species composition of the contemporary Amazon forest differs significantly between different localities (ter Steege et al., 2013), so reconstructing past biodiversity requires sampling across the entire region. Thus, non-similarity between paleo-biota from tropical and subtropical latitudes (Jaramillo and Cardenas, 2013) does not preclude the possibility that both latitudes hosted a continuous Amazon-type rainforest.

2. What is the history of tropical South American climate from the Late Cretaceous to today? Does the Cenozoic thermal history of the Amazon region mirror the global history that we deduce from the deep-sea oxygen isotopic record (Zachos et al., 2001)? Were thermal optima relatively wet or dry periods? The Held and Soden (2006) model predicts a wetter Amazon in past thermal maxima and a drier Amazon in past cold periods. Was this in fact the case? Or did an east–west equatorial precipitation dipole persist throughout the whole Cenozoic as has been reconstructed from late Quaternary speleothems (Cheng et al., 2013)? Did the progressive widening of the Atlantic Ocean and the developing east–west equatorial Pacific zonal sea surface temperature gradient during the Cenozoic imprint themselves on the hydrologic record of the Amazon? Is there any evidence for increasing dryness during the Cenozoic as has been reconstructed for other tropical localities (e.g., Sepulchre et al., 2006)?

3. What is the history of Andean uplift and erosion as recorded in Andean foreland basins? The Acre foreland basin is ideal for this purpose, because it is sufficiently proximal to the Andes to receive detrital input, yet sufficiently distal from the Andes to have a relatively slow and continuous rate of accumulation of finer-grained sediment most amenable to paleoecological study. We expect Andean provenance to be well recorded in both the Acre and the Solimões basins. Specifically we will test the alternative hypotheses (1) that the portion of the Andes located to the west of this region was high-standing and provided sediment to the Acre Basin throughout the entire Cenozoic, or (2) that the Andes only underwent significant uplift in the Late Miocene.

4. When did west-to-east hydrologic continuity develop between the Amazon basin and the equatorial Atlantic?

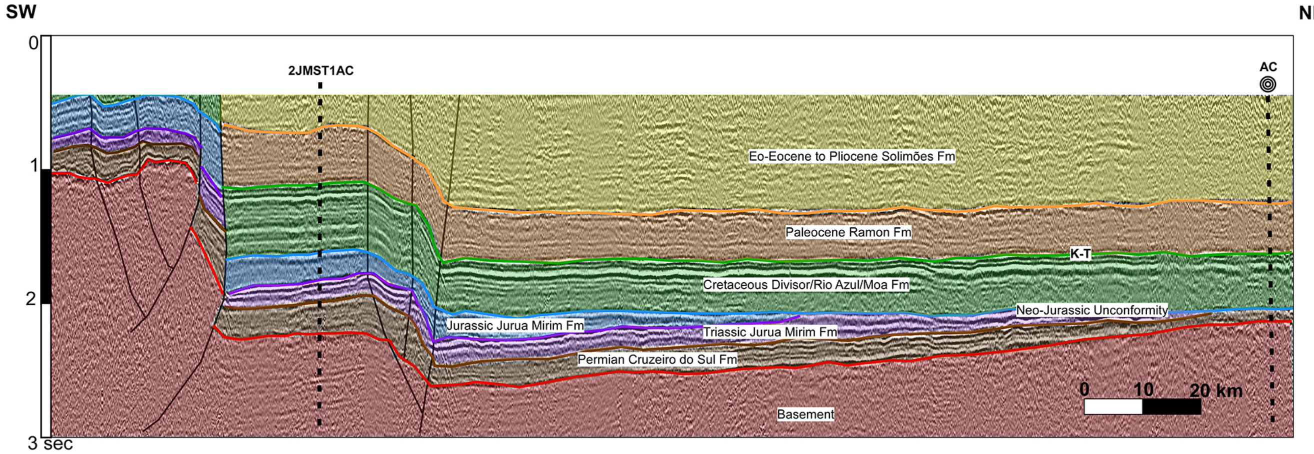

Figure 2. Seismic reflection profile from the Acre Basin (location of line shown in Fig. 1). The proposed drill hole location (AC) and previous drill hole location (2JMST1AC) are shown.

> Did the Purus Arch act as an ancient hydrologic divide between eastward and westward drainage? Did the Gurupá Arch form the ultimate divide between the western Amazon drainages and the Atlantic Ocean? Did these structural arches serve as geographic barriers as posited by Patton et al. (2000)? Did the main-stem Amazon or its major tributaries present barriers to taxa inhabiting opposite banks of the rivers (e.g., Ribas et al., 2011)? Can we date the origins of the through-flowing Amazon, providing better constraints for molecular dating of taxonomic divergence (Baker et al., 2014)?

5 Potential new drilling targets emerging from workshop discussions

The thickest volumes of the entire Central Atlantic Magmatic Province (CAMP, Marzoli et al., 1999) are preserved in the sedimentary basins of the Amazon. Workshop participant, Andrea Marzoli, discussed the exciting potential for drilling into this key stratigraphic unit to uncover its volume, origins, and timing of formation. CAMP magmatism caused rapid global perturbations through the emission of volcanic gases and was associated with the break-up of Pangaea, the opening of the Atlantic Ocean, and the mass extinction event at the Triassic–Jurassic boundary (Marzoli et al., 2004; Schoene et al., 2010; Ruhl et al., 2011). Intruded magmas occur within the Paleozoic sedimentary sequences of the Amazon and Solimões basins (Fig. 3) and reach up to a kilometer in thickness and can be traced over distances of nearly 1000 km. Geochemical and geochronological analysis of these extensive units can be used to test hypotheses regarding the origins of CAMP and its global impacts.

The outcropping sedimentary formations of the Amazon basin also host one of the largest aquifers in the world (Wahnfried and Soares, 2012). Workshop participant, Ingo Wahnfried, argued that the drilling of the Cenozoic and older sediments of the Amazon region will provide important constraints on the volume, age, geochemistry, flow rates, and residence time of groundwater units and the connectivity of surficial and shallow units with deeper transmissive layers. The aquifers are important conduits between surface and the subsurface environments, and access to aquifers may also provide important insights into biogeochemical processes, as well as the deep biosphere and the diversity of Amazonian subsurface microbial communities.

6 Site selection and logistics of drilling

We have reviewed seismic reflection and well log data from all four of the continental Brazilian Amazon basins, and we have identified five continental drilling sites, all easily accessible, located on pre-existing seismic lines, and located near pre-existing drill holes with available well log and lithologic data. We are working with the Brazilian drilling company Geosol to develop a detailed proposal for carrying out the drilling operations, employing either a Boart Longyear LF or Atlas Copco CT 20 drill rig. Both have capabilities to drill to more than 1500 m with HQ diameter cores or nearly 2500 m with N diameter cores. The drill sites will all be located on the margins of large navigable rivers (the Juruá, the Amazon, the Straits of Breves), allowing transport of equipment and personnel by barge. Drilling will involve offloading the drilling vehicle at a port or temporary landing and installation on a pre-prepared drilling pad. All personnel will be housed in a hotel boat adjacent to the drill site. All drilling will be undertaken with blow-out prevention due to the possibility of encountering shallow gas accumulations in this region. Drilling muds will be chosen with consideration to minimizing contamination for organic geochemistry while maximizing core recovery and drilling rate.

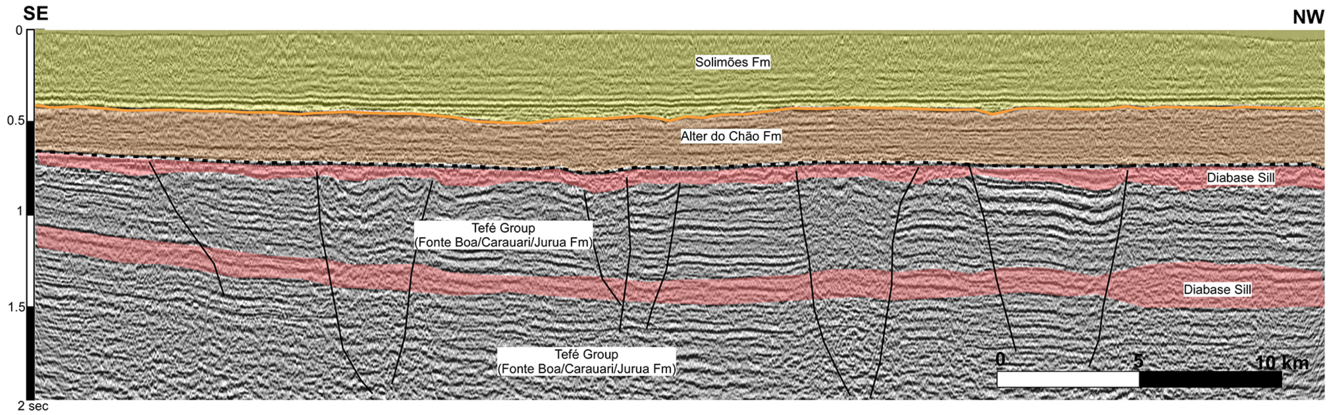

Figure 3. Seismic reflection profile from the Solimões Basin (location of line shown in Fig. 1). Here, the Alter do Chão Formation is illustrated to be Cenozoic (Caputo, 2011), not Cretaceous, as previously believed. Multiple diabase sills and interbedded sediments unconformably underlie Cenozoic sediments in this region. The proposed (SB) drill hole will encounter the same stratigraphic column as shown in the seismic line, but is located more accessibly on the Rio Juruá.

In the westernmost Acre Basin, thick Cenozoic foreland basin sequences will require our deepest drilling, perhaps 2 km total depth, in order to reach the Cretaceous–Paleogene boundary (Fig. 2). In the Solimões Basin site (Fig. 3), a thinner sequence of the Mio-Pliocene Solimões Formation conformably overlies the Paleocene-to-Miocene-age (Caputo, 2011) Alter do Chão Formation that, in turn, unconformably overlies the "Penatecaua" diabase sills. In this site, we aim to recover a sequence of 750 m of Cenozoic sediments overlying a complete sequence (ca. 900 m total) of four diabase sills and interbedded sediments.

On the eastern flank of the Purus Arch, we will drill a site in the western Amazon basin where the Cenozoic sequence is substantially thinner than in the Solimões Basin. A second Amazon site will be located in the far eastern part of the basin on the western flank of the Gurupá Arch, where Cenozoic sediments are appreciably thicker than farther west. This latter site will be paired with a site on the eastern flank of the Gurupá Arch in the northwestern part of the Marajó Basin, where the Cenozoic sequence is ∼ 1 km thick, shows considerable marine influence, and can be dated by marine biostratigraphy. It is expected that correlation will be possible across the Gurupá Arch over the small distance separating these two sites. In the Marajó site, we expect that the first appearance of detritus with Andean provenance will allow us to date the onset of trans-continental drainage. Elsewhere in the Marajó Basin, rapid (and ongoing) subsidence led to deposition of a Cenozoic sequence as much as 10 km thick, far beyond our drilling capabilities.

Dating the Cenozoic, mostly fluvial, sediments of the Amazon has been challenging. We expect this to be undertaken by a combination of paleomagnetic stratigraphy, palynostratigraphy, U–Pb geochronology, and marine biostratigraphy in the eastern sites proximal to the Atlantic Ocean. Key measurements to be undertaken on all drill cores are pollen identification and quantification to determine biodiversity and its change through time (Jaramillo et al., 2006, 2010); organic geochemical measurements that record past climate, yet are relatively insensitive to diagenetic alteration (Freeman and Pancost, 2014); microfossils and geochemical measurements on carbonate units that can differentiate between fresh, brackish, and marine environments (Gross et al., 2011, 2013); and provenance studies using U–Pb or Nd–Sm or other measurements that will allow dating of connectivity of basins across the continent (Mapes, 2009).

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Time-lapse characterization of hydrothermal seawater and microbial interactions with basaltic tephra at Surtsey Volcano

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Abstract. A new International Continental Drilling Program (ICDP) project will drill through the 50-year-old edifice of Surtsey Volcano, the youngest of the Vestmannaeyjar Islands along the south coast of Iceland, to perform interdisciplinary time-lapse investigations of hydrothermal and microbial interactions with basaltic tephra. The volcano, created in 1963–1967 by submarine and subaerial basaltic eruptions, was first drilled in 1979. In October 2014, a workshop funded by the ICDP convened 24 scientists from 10 countries for 3 and a half days on Heimaey Island to develop scientific objectives, site the drill holes, and organize logistical support. Representatives of the Surtsey Research Society and Environment Agency of Iceland also participated. Scientific themes focus on further determinations of the structure and eruptive processes of the type locality of Surtseyan volcanism, descriptions of changes in fluid geochemistry and microbial colonization of the subterrestrial deposits since drilling 35 years ago, and monitoring the evolution of hydrothermal and biological processes within the tephra deposits far into the future through the installation of a Surtsey subsurface observatory. The tephra deposits provide a geologic analog for developing specialty concretes with pyroclastic rock and evaluating their long-term performance under diverse hydrothermal conditions. Abstracts of research projects are posted at http://surtsey.icdp-online.org.

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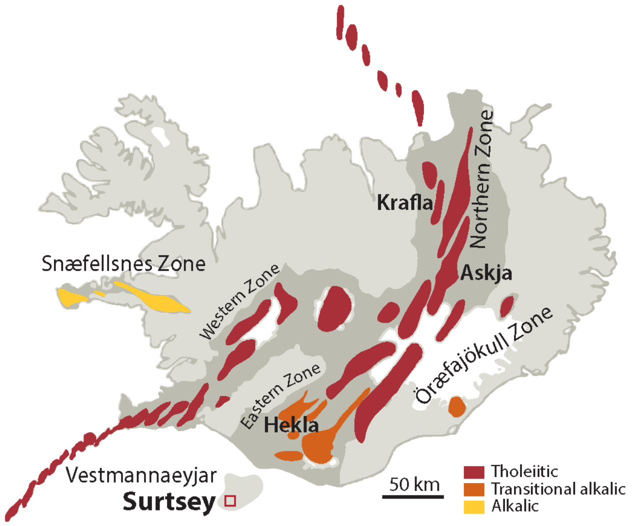

Figure 1. The location of Surtsey Volcano within the southernmost extension of the Eastern Icelandic rift zone (scale bar of 50 km; after Trønnes, 2002). Colors refer to compositional trends in basaltic rocks (Jakobsson et al., 2008).

Figure 2. Surtsey Volcano in eruption, 30 November 1963 (Terry Mann, courtesy of Robert Carson).

1 Introduction

The very young volcanic island of Surtsey, which formed over a 3.5-year episode of eruptions along the southern offshore extension of the SE Icelandic volcanic rift zone (Figs. 1, 2), represents a world-class example of a rift zone volcano that has grown from the seafloor in historic time. The Surtsey eruption was thoroughly documented beginning in November 1963, when a plume of ash first broke the sea surface, until the termination of subaerial lava flow activity in June 1967. Surtsey was designated a UNESCO World Heritage site in 2008 and "has been protected since its birth, providing the world with a pristine natural laboratory" for study of earth and biological processes (Baldursson and Ingadóttir, 2007). An International Continental Drilling Program (ICDP) workshop on Heimaey Island in October 2014 convened 24 scientists from 10 countries and representatives from the Surtsey Research Society, who developed the scientific objectives of the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and INnovative Concretes (SUSTAIN) drilling project (Jackson, 2014). The project will include the eventual installation of an in situ Surtsey subsurface observatory for monitoring hydrothermal microbial life and changes in the physical and compositional properties of associated hydrothermal fluids, which will complement the 50 years of observations of plant and animal life on the surface of Surtsey.

The 181 m deep hole drilled within the eastern tephra cone in 1979 (Fig. 3a) was sponsored by the US Geological Survey and the Icelandic Institute of Natural History. It has provided well-constrained information about the substructure and stratigraphy of the volcano, as well as the nature of its hydrothermal system, which continues to be manifested by steam vents at the surface (Jakobsson and Moore, 1986, 1992; Jakobsson et al., 2013). Investigations of the core and downhole temperature measurements described the petrologic characteristics of the basaltic tephra, partially altered to palagonite tuff, the thermal conditions and nature of hydrothermal alteration, and the authigenic mineral growth of a rare aluminous calcium-silicate-hydrate and zeolite mineral assemblage above and below sea level (Fig. 3b). These minerals, Al-tobermorite and phillipsite, have cation exchange capabilities for certain radionuclides and heavy metals and have been the focus of laboratory syntheses of concretes for hazardous waste encapsulations (Komarneni and Roy, 1983; Komarneni, 1985; Trotignon et al., 2007; Cappelletti et al., 2011; Coleman et al., 2014). In the SUSTAIN drilling project, time-lapse investigations of dynamic secondary mineral assemblages in the altered tephra deposits will yield information from a geological analog for the long-term performance behavior of specialty concretes formulated with pyroclastic rock. The results of these investigations will advance technological developments initiated by ancient Roman engineers, who developed pozzolanic concretes with this same mineral assemblage that have maintained their integrity despite centuries-long exposure to seawater (Brandon et al., 2014). A recent study of hot fluids in the 1979 drill hole (Fig. 3b) has identified for the first time potentially indigenous thermophilic bacteria and archaea deep in the center of an isolated Neogene volcanic island (Marteinsson et al., 2015). In the SUSTAIN project, studies of microbial colonization of the altered subterrestrial tephra and hydrothermal fluids could provide new insights into archaeal lineages in the very young biosphere and, possibly, contribute to understanding the nature of the archaeal ancestor of eukaryote organisms (Spang et al., 2015).

Two holes through the 50-year-old deposits, designed in collaboration with the Icelandic National Planning and Environment Agencies to protect the sensitive habitats of the Surtsey Natural Reserve, will be drilled at a site within ∼5 m of the 1979 hole (Fig. 3a). A vertical drill hole, ∼210 m deep, will explore pore water chemistry, microbiology, and microbiological–water–rock interactions and compare the present state of hydrothermal alteration with that in the 35-year-old drill core. The hole will be cased with anodized aluminum for future Surtsey subsurface observatory studies. A ∼300 m long inclined hole with steel casing will intersect tephra deposits, dikes and other vent facies beneath the crater; provide additional information on deep stratigraphy and submarine structure below the 181 m depth of the 1979 hole; and investigate the changing temperatures and the compositions of whole-rock, glass and mineral assemblages of the hydrothermal system. Slim-hole logging sondes will be deployed from a motorized winch to the base of the holes at 200–300 m depth. Sensors will acquire equilibrated temperature measurements, total natural gamma to log lithological variations; electrical resistivity and self-potential to show variations in fluid salinity and influences of alteration processes; and sonic P-wave velocity and magnetic susceptibility to show possible variations in compaction, alteration, and authigenic mineralogy. Core segments from the inclined hole will be oriented to ±1° of azimuthal accuracy to further evaluate the internal structure, stratigraphy, composition and mineralogy of the volcanic edifice.

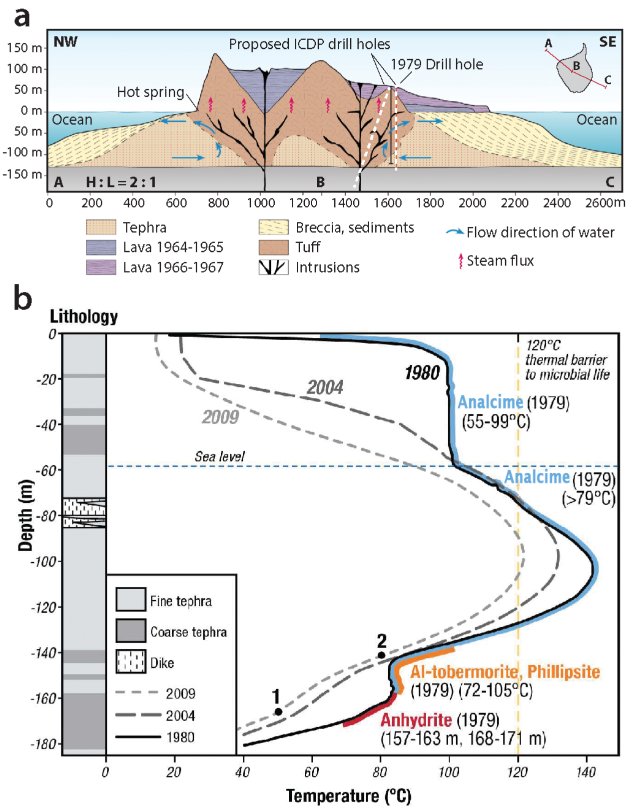

Figure 3. Hydrothermal alteration of Surtsey deposits (after Jackson, 2014). **(a)** Schematic cross section (Jakobsson et al., 2009) shows inferred feeder dikes, palagonitization of basaltic tuff in 2004, the 1979 drill hole, and the two planned ICDP drill holes. **(b)** Temperatures in the 1979 hole. Lines adjacent to the 1980 curve show greatest abundance of authigenic analcite (blue), Al-tobermorite and phillipsite (orange), and anhydrite (red). Downhole water sampling in 2009 and microbiological analyses reveal diverse subterrestrial bacterial sequences and *Methanobacteriales*blackbox[CE]Please note that when written individually only the "genus" devision names withing the taxonomic clasification system are italicized, it seems that Methanobacteriales refers to an "order" of the system. For future reference, does Methanobacteriales fall under a different set of taxonomy and nomenclature rules?-like archaeal sequences at 172 m (54 °C) (site 1) and an archaeal community dominated by *Archaeoglobus*-like 16S rRNA sequences at 145 m (80 °C) (site 2) (Jakobsson and Moore, 1986; Olafsson and Jakobsson, 2009; Marteinsson et al., 2015).

2 Workshop goals

The SUSTAIN drilling project will use the natural laboratory of the Surtsey tephra above and below sea level, and interdisciplinary volcanological, microbial, geochemical, mineralogical, and geoarchaeological research programs to undertake scientific investigations situated within the larger ICDP research themes of the evolution of hydrothermal seawater–rock interactions in rift zone volcanism, the succession of early microbial life, and the development of industrial resources, using the alteration processes of palagonitized tuff as models for creating sustainable, high-performance concretes with pyroclastic rocks.

2.1 Subaerial and submarine structures of the type locality of Surtseyan volcanism

Descriptions of the episodic eruptions at Surtsey from 1963 to 1967 provide the most comprehensive record of Surtseyan-style emergent volcanic activity and island rift zone volcanism in the world (Thórarinsson, 1967). Questions remain,

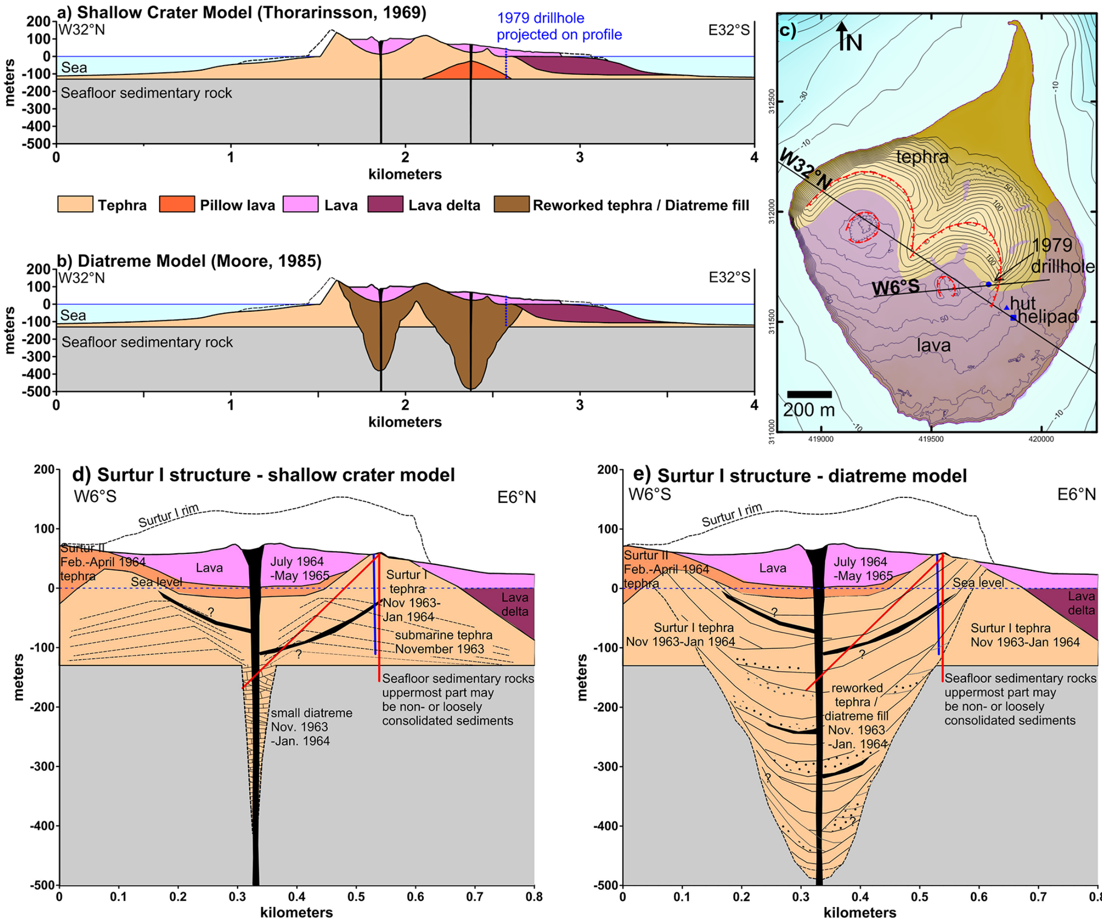

Figure 4. Structural models of Surtsey, showing the shallow crater hypothesis **(a, d)** (Thórarinsson, 1969) and the diatreme hypothesis **(b, e)** (Moore, 1985). Red lines on **(d)** and **(e)** show the planned drill holes. Although the occurrence of a layer of pillow at the bottom of the formation cannot be ruled out (model shown in **a**), no pillow mound is included in **(d)** as neither was it detected in the 1979 drill hole nor in gravity modeling (Thorsteinsson and Gudmundsson, 1999). The geological map of Surtsey **(c)** shows the helipad, the Pálsbær II hut, and 1979 drill site.

however, about the earliest submarine part of the edifice, which was not observed during initial studies of the volcano (Fig. 4). The role of seawater interaction with hot magma and temporal variations in magmatic volatile content in driving subaerial explosive eruptions will also be investigated. New drilling will clarify Surtsey's early history and submarine structural anatomy and provide interdisciplinary perspectives into explosive eruptive processes and how volcanic facies, structural discontinuities, pyroclast size and vesicularity provide a template for hydrothermal fluid flow, heat transfer, diagenetic and biogenetic alteration processes, and temporal changes in porosity and rock physics properties.

2.2 Fluid geochemistry and microbial colonization of subsurface deposits

Surtsey is an isolated oceanic island that has provided an exceptionally well-monitored laboratory of world-wide significance for the investigation of biological colonization and succession on and in basaltic tephra deposits. Furthermore, the temperature range recorded in the 1979 hole (Fig. 3b) is ideal for studying the extreme temperature conditions of chemosynthetic life. A subsurface biome comprising bacteria and archaea has recently been observed in fluids extracted from the 1979 hole below 145 m depth (Fig. 3b). This subsurface microbial community is quite possibly indigenous, since it occurs below a $>120\,^{\circ}C$ thermal barrier at 100 m depth that prevents the downward dissemination of surface organisms (Marteinsson et al., 2015). Microbial colonization has been recognized as one of the primary drivers of alteration in ridge crest seafloor basalts and has important implications for global element budgets, seafloor and seawater exchange, and biogeochemical cycles (Thorseth et al., 2001; Furnes et al., 2007; Santelli et al., 2008; Edwards et al., 2012). Investigating the nature and extent of the subseafloor biosphere has become an important scientific goal of research programs, including the International Ocean Discovery Program (IODP). It is, however, exceedingly difficult and costly to investigate these processes through drilling at depths of oceanic ridge systems. Drilling into Surtsey's active hydrothermal system will provide a new window into the subterrestrial biome at relatively low cost and in an exceptionally well-constrained drill site that already has a proven record of success. The subseafloor pressure at the Surtsey subsurface observatory at < 0.2 km depth will be lower than that typical of the neovolcanic zone of mid-ocean ridges at ~ 2.5 km depth. This means that more phase separation (boiling) can occur in this shallow environment at temperatures relevant to microbial metabolism. Because many of the energy-rich substances capable of supporting autotrophic life (e.g., H_2, H_2S, CH_4) partition into the vapor phase, we may expect to see higher redox gradients and more spatial diversity in microhabitats in this environment compared to those that could be investigated on the ridge crest.

2.3 Evolving hydrothermal processes and tephra alteration

Comparisons of new cores with the 1979 core and original samples of the newly erupted deposits will give precise information about the time-integrated evolution of fluid–rock interactions. These include the alteration of basaltic glass to form palagonite, at variable temperature and fluid chemistry, and associated secondary mineral nucleation and growth (Fig. 3a). Palagonite is a metastable alteration product of fresh basaltic glass that has interacted with aqueous solutions and lost Si, Al, Mg, Ca, Na and K, gained H_2O, and become preferentially enriched in Ti and Fe (Stroncik and Schmincke, 2002). Recent compositional analyses of the Surtsey magma series provide a reference for the original compositions of these deposits (Schipper et al., 2015). The ongoing hydrothermal alteration and lithification of tephra has great relevance to the longevity of the island since it is the progressive formation of palagonitized tuff, rather than capping lavas, that provides resistance to incessant marine erosion (Moore et al., 1992; Jakobsson et al., 2013). The Surtsey hydrothermal system is one of the few localities worldwide that is actively producing an authigenic Al-tobermorite and zeolite assemblage (Jakobsson and Moore, 1986). Tobermorite, $Ca_5Si_6O_{16}(OH)_2{\cdot}4H_2O$, with 11 Å c axis interlayer spacing is formed by the action of hydrous fluids on basic igneous rocks, such as the amygdules in Paleogene lavas in contact with hydrothermal fluids on the Island of Skye, Scotland (Livingstone, 1988). It also occurs among the alteration products at the cement–rock interface of toxic and nuclear waste repositories (Gaucher and Blanc, 2006). It is a candidate sorbent for nuclear and hazardous waste encapsulation owing to its ion-exchange behavior which arises from the facile replacement of labile interlayer cations (Coleman et al., 2014). Al-tobermorite and phillipsite also occur as the principal cementitious mineral phases in the volcanic ash–lime mortar of ancient Roman concrete harbor structures. These mortars bind zeolitic tuff and carbonate rock coarse aggregate in piers, breakwaters, and fish ponds that have remained stable in Mediterranean seawater for 2000 years (Jackson et al., 2013a, b). Little is known, however, about how hydrothermal chemistry and phase-stability relationships in Al-tobermorite and zeolite mineral assemblages evolve as a function of time, temperature, fluid interactions, and microbial activity. The new cores will therefore provide a real-time geologic analog for understanding the evolving microstructures and macroscopic physical properties of tuff and sustainable concrete prototypes with pozzolanic pyroclastic rocks under the variable hydrothermal conditions of the engineered barriers of waste repositories.

3 Characterization of the 50-year-old deposits

The collaborative research investigations to be undertaken by the scientific team of the SUSTAIN drilling program focus on three ICDP research themes: volcanic systems and geothermal regimes, the geobiosphere, and natural resources as applied to pyroclastic rock concretes in the sustainable built environment.

3.1 Anatomy of 1963–1967 Surtsey deposits and eruptive processes

The subaerial tuff cones of Surtsey are constructed from deposits produced by intermittent tephra-finger jets and from continuous uprush eruptions. Continuous uprush lasted for several minutes to several hours and produced eruption jets 100–250 m in diameter and 500–2000 m in height forming up to 9 km high eruption columns (Thórarinsson, 1967). The new drill holes should clarify whether the lower part of the edifice contains a mound of submarine pillow lavas (Fig. 4a) (Thórarinsson, 1967) or tephra (White and Houghton, 2000) that preserves the initial submarine depositional phase of the eruption, or a deep funnel filled with slumped and down-faulted subaerial deposits (Fig. 4b) (Moore, 1985). We can therefore test which of two contrasting models best represents the true structure of the island: the shallow crater model (Fig. 4a) (Thórarinsson, 1967; Jakobsson and Moore, 1992; Jakobsson et al., 2013) where any diatreme that may have formed is narrow, leaving the pre-eruption seafloor relatively intact underneath the volcanic edifice, or the diatreme model (Fig. 4b) (Moore, 1985) that has wide, funnel shaped, tephra-filled diatremes that extend a few hundred meters into the pre-eruption seafloor. The new oriented cores should help us define these volcanic structures. For example, do the primary layering and pre-solidification slump planes dip steeply inward toward the vent of the volcano (Fig. 4e) as observed in unoriented cores from the 1979 drill hole (Moore, 1985) or do beds dip gently outward away from the vent (Fig. 4d) as suggested by a shallow crater model? Deepening of the inclined hole may resolve the disparity in the two models regarding the width of the subseafloor diatreme structure and may possibly intersect the outer wall of the diatreme if it is sufficiently narrow. Analyses of core from the inclined hole should also provide information about how the onset of fragmentation, submarine transport of tephra, and deposition in the submarine environment differs from what is represented in subaerial deposits. The extent to which Surtsey's activity was predominantly phreatomagmatic, versus the degree to which it involved substantial volatile-driven magmatic explosivity has important implications for predicting potential hazards to air traffic from future Surtseyan-type eruptions. These processes can be clarified with rigorous analysis of deposits (e.g., Schipper et al., 2010, 2015) combined with experiments using remelted material from the island (Büttner et al., 2002).

3.2 Monitoring hydrothermal processes 50 years after the Surtsey eruptions

The current model for Surtsey's hydrothermal system hypothesizes that cooling of dike intrusions in the eruptive centers of the eastern and western craters (Stefansson et al., 1985) provides the heat to drive hydrothermal convection, which results in palagonitization of the tephra and induration of the core of the island (Fig. 3a). The high heat of vaporization of water means that significant heat transfer occurs isothermally by release of steam through the tephra pile, as indicated by the isothermal (100 °C) portion of the temperature profile measured in 1980 before the well bore filled with water (Fig. 3b). The new cores will further clarify the extent and nature of the intrusive system and how early residual heat in the tephra might have influenced hydrothermal processes. New studies of the cooling hydrothermal system, the roles of meteoric water and tidal flux, salinity, pH, sulfur cycling, and possible microbial oxidation of iron in both new holes will further elucidate water–rock interactions, and the progressive palagonitization and consolidation of glassy basalt deposits through abiotic and/or biotic processes (Walton, 2008; Pauly et al., 2011). Determination of rates of reaction and phase-stability relationships in the evolving Surtsey tuff as a function of time, temperature, and fluid interactions will provide an exceptionally well-constrained geological analog for innovative, pyroclastic rock concrete encapsulations of hazardous wastes that use ancient Roman concrete as a prototype (Jackson et al., 2013b). The formation of Al-tobermorite and phillipsite in massive Roman seawater concrete harbor structures is in part controlled by elevated temperature that arises during formation of poorly crystalline calcium-aluminum-silicate-hydrate (C-A-S-H) cementitious binder due to exothermic reactions, but these processes are poorly understood (Jackson et al., 2013a). The ion-exchange selectivity of the 11 Å tobermorite and zeolitic mineral assemblages for Cs^+ and Sr^{2+} will be determined experimentally on samples of Surtsey tuff at certain critical horizons (Fig. 3b) (Cappelletti et al., 2011; Coleman et al., 2014). The changes in macroscopic rock physics and mechanical properties, such as strength and elastic moduli, that these rock–fluid interactions produced in the pyroclastic deposits will also be investigated (Vanorio and Kanitpanyacharoen, 2015). These processes have implications for the larger-scale stabilization of the Surtseyan-style volcanic edifice against erosion, including subglacial edifices formed in eruptions under ice (Jarosch et al., 2008).

3.3 Active microbial processes and fluid geochemistry

In recent years the deep biosphere has been shown to be an immense habitat for microbial life, and these findings have wide reaching implications for global geochemical cycling (Orcutt et al., 2011). Although there is increasing exploration of the deep biosphere, mainly due to advances in drilling technologies and underwater equipment, one fundamental environment remains unexplored: the "zero age" upper crust. This province is exceptionally interesting since it is here that the first microbial colonization and interaction with basaltic rocks takes place. Exploration of the microbial colonization of Surtsey tephra could therefore give otherwise unavailable insights into the origins of rock-dwelling microorganisms. The diversity, abundance, and function of potentially endemic communities of microorganisms will be analyzed by DNA extraction and next generation sequencing of metagenomes and 16S rRNA genes. The functioning of the microbiome will be investigated by transcriptomic analysis and strain isolations (Marteinsson et al., 2015).

Assessments of the geochemical composition of hydrothermal seawater, reaction progress associated with water–rock–microbiological interaction and inorganic chemical energy available in the hydrothermal system, will be combined with equilibrium reaction models to describe affinities for chemosynthesis and tephra alteration and provide constraints on the potential energy available for microbial metabolism. The design of the Surtsey subsurface observatory is similar to that of observatories installed during recent IODP expeditions (Fisher et al., 2011; Edwards et al., 2012). After drilling, incubation chambers (e.g., Toner et al., 2013) will be deployed inside slotted sections of the aluminum casing to facilitate further microbial, geochemical and hydrological studies in isolated sections of the drill hole above sea level (< 60–70 m below the surface (mbs) at the drill site), in the highest temperature regime (70–140 mbs), and below the high temperature regime (> 140 mbs) (Fig. 3b). The new studies of potentially indigenous subsurface microbial life in the vertical hole will be the first systematic, longitudinal study of microbial colonization of an isolated neovolcanic island at successive depths from the surface to the seafloor.

Participants of the ICDP SUSTAIN workshop

The drilling project collaborators and science team, as well as abstracts describing scientific objectives, are posted at http://surtsey.icdp-online.org.

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Advancing subsurface biosphere and paleoclimate research: ECORD–ICDP–DCO–J-DESC–MagellanPlus Workshop Series Program Report

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Abstract. The proper pre-drilling preparation, on-site acquisition and post-drilling preservation of high-quality subsurface samples are crucial to ensure significant progress in the scientifically and societally important areas of subsurface biosphere and paleoclimate research. Two of the four research themes of IODP and ICDP and one of the four research areas of the Deep Carbon Observatory (DCO) focus on the subsurface biosphere. Increasing understanding of paleoclimate is a central goal of IODP and incorporated within the scope of the IMPRESS program, the successor of the IMAGES program. Therefore, the goal of our IODP–ICDP–DCO–J-DESC–MagellanPlus-sponsored workshop was to help advance deep biosphere and paleoclimate research by identifying needed improvements in scientific drilling planning and available technology, sample collection and initial analysis, and long-term storage of subsurface samples and data. Success in these areas will (a) avoid biological and other contamination during drilling, sampling, storage and shipboard/shore-based experiments; (b) build a repository and database of high-quality subsurface samples for microbiological and paleoclimate research available for the scientific community world-wide over the next decades; and (c) standardize, as much as possible, microbiological and paleoclimate drilling, sampling and storage workflows to allow results and data to be comparable across both space and time. A result of this workshop is the development and suggested implementation of new advanced methods and technologies to collect high-quality samples and data for the deep biosphere and paleoclimate scientific communities to optimize expected substantial progress in these fields. The members of this workshop will enhance communication within the scientific drilling community by crafting a handbook focused on pre-drilling, drilling and post-drilling operations.

1 Scientific rationale

For nearly two decades, a multidisciplinary, international effort has been conducted to describe the living subsurface biosphere. Although most research was conducted in the marine systems with the support of the International Ocean Discovery Program (IODP) and its predecessors (DSDP, ODP), exploration of the terrestrial subsurface biosphere through the International Continental Scientific Drilling Program (ICDP) has substantially increased in recent years. Microbial communities have been characterized in numerous sediment types representing a multitude of geologic ages, geochemical conditions, and geophysical constraints (IODP – Parkes et al., 2005; Schippers et al., 2005; Morono et al., 2011; Mills et al., 2012a; ICDP – Heim, 2011; Colwell and D'Hondt, 2013; Lau et al., 2014). As IODP embarks on a new decade, the time is right to coalesce the strengths and address the weaknesses from previous studies to re-develop and implement a plan to improve and standardize subsurface biosphere exploration. Due to the more individual or small group nature of drilling projects within ICDP, the European Consortium for Ocean Research Drilling (ECORD) and the Deep Carbon Observatory (DCO), the need for standardized biological sampling, processing and analysis becomes even more important.

The demand for biological samples has and will continue to increase as a result of the larger commitment to biology in the DCO and the new science plans of both IODP (2011) and ICDP (2014). The biological scientific goals within these groups focus on (a) the origin, composition and global significance of subsurface communities, (b) the scarcity of nutrients and energy and the limits of life in the subsurface, (c) the impact of environmental change on subsurface ecosystems and biodiversity and (d) the impact of subsurface communities on paleo-environmental and paleoclimate proxies, minerals and hydrocarbon reservoirs. Without the ability to compare results of multiple expeditions and access to properly acquired samples, these goals cannot be achieved. The biosphere community is aware of this challenge and understands the need for standardizing sample collection procedures, initial analysis protocols and long-term storage techniques (Orcutt et al., 2013; Kieft et al., 2015). We recognize that education of the broader drilling community is also required as many efforts related to biological sampling and characterization are seen as disruptive to normal core flow and description.

A unique challenge for the deep biosphere community has been fully communicating our requirements and resources to the drilling community. Biologists understand the need for collaborative data sets that characterize the chemical, physical and geological parameters of the sample. In many ways the drilling community views the biologist as a sink for drilling data; we use the data others produce but contribute little information in return to overall sample analysis. However, biologists can be a valuable source of subsurface data when consulted during core description and preservation efforts. By including biologically relevant chemical, physical and geological parameters within standard data sets, biologists can determine active microbial processes that may have altered or continue to alter parameters measured by other groups. The presence of active biological processes within retrieved samples can also have detrimental effects on legacy cores (Mills et al., 2012b). It is time for other disciplines to engage with biologists and biogeochemists in discussions about the effects of a living biosphere on the subsurface environment. For example, the application of proxies in paleoclimatology has become crucially important to reconstruct paleo-environmental settings and paleoclimate change. Since these proxies are based on organic compounds (biomarkers) and abundances and/or speciation of inorganic constituents, including stable isotope compositions, we must understand how these geochemical entities are affected by the microbial communities within the subsurface biosphere.

To further advance biosphere exploration in the scientific drilling community, a multidisciplinary team, including a molecular biologist, an ecologist, geochemists, and geologists, from nine countries assembled in Seoul, South Korea. The group represented leaders in the field of subsurface biosphere exploration in both the marine and terrestrial systems and possessed knowledge of prior similar workshops and initiatives to standardize subsurface biosphere techniques. The motivation for this workshop emerged during presentations and discussions at the Chikyu+10 meeting (Tokyo, 21–23 April 2013) and represents a successful extension from that meeting. Initial plans for this workshop exclusively focused on IODP-related research, but during the ICDP Science Conference in Potsdam, Germany (11–14 November 2013), it became clear that subsurface biosphere exploration faces the same challenges in both the marine and terrestrial realm. Therefore, the conveners broadened the workshop to cover additional programs including ICDP, DCO, and IMPRESS. Together these groups, and new ones to follow, have the potential to make a significant impact in subsurface biosphere research, the fastest developing field within the drilling community. Results from this workshop will be crucial in the development of the procedures required to accomplish the goals set forth in the new science plans and promoted through new initiatives.

One of our main goals in organizing this workshop was to advance the efforts of previous workshops. The 7th IODP Scientific Technology Panel that met on 28–30 July 2008 in Edmonton, Canada, expressed the need to standardize the biological sampling process and improve mechanisms for completing biological research within IODP. While procedural and policy changes have been implemented as a result of this 2008 meeting, several key challenges remained insufficiently addressed, including standard sub-sampling techniques for frozen samples, time- and redox-sensitive measurements, and submission of microbiology data and samples. ICDP first addressed subsurface biosphere research at their 2005 Science conference (Horsfield et al., 2007). In Potsdam 2009, an international workshop on the integration of deep biosphere research into ICDP listed potential drilling targets as well as technical and logistical prerequisites (Mangelsdorf and Kallmeyer, 2010). The growing strengths of DCO and IMPRESS provide additional momentum to subsurface biosphere exploration while presenting new and diverse challenges that must also be considered. Incorporating individuals present at these and other past meetings as well as those active within these different research communities was viewed as vital to the success of our workshop. In addition, individuals knowledgeable of new techniques and technologies were invited to address needs realized since the conclusion of the previous meetings. An open format for the workshop provided time for these groups to address past, present and future needs of the growing subsurface biosphere community.

2 The workshop

The Advancing Subsurface Biosphere and Paleoclimate Research workshop took place in Seoul, South Korea, on 21–23 August 2014, directly before the International Society for Microbial Ecology (ISME) meeting, also in Seoul. Twenty-eight junior and senior scientists with experience in the geomicrobiological and biogeochemical components of the IODP, ICDP, DCO and IMPRESS (the successor of IMAGES) programs representative of the global community of subsurface microbiology, participated in this workshop and, for the first time, were able to speak with one solid voice. The idea for this workshop was developed during the Chikyu+10 workshop in April 2013, but had roots in many workshops, meetings and discussions over the last several years. Since the Chikyu+10 workshop, the idea to have a community discussion on standard protocols for microbiological drilling, sample handling and long-term sample storage developed rapidly with the interest and support of ICDP and DCO. Timing was important for these discussions since IODP, ICDP and DCO are at the beginning of new 10- and 5-year science plans with large geomicrobiological and paleoclimate components.

The overall aim of our workshop was to develop shared sampling and long-term storage strategies partly based on already existing white and scientific papers and to implement these strategies through standardized protocols for all drilling platforms, i.e., “traditional drilling” with the JOIDES Resolution, Chikyu and MSP/ICDP platforms. A decision was made during the workshop planning to expand the goal for standardization to much less expensive seabed drilling and long piston core operations from additional research vessels.

Initial workshop discussions were dedicated to providing background information on the current state of deep life research and proxy-based paleoclimatology within long-term scientific plans for IODP, ICDP, DCO and IMPRESS. In addition, presentations on subsurface microbiology and proxy-based paleoclimatology highlighted the benefits of conducting geomicrobiological and paleoclimate research by acquiring high-quality microbiological samples, even when the expedition may focus on other scientific disciplines. At the end of day 1 and the start of day 2, most participants gave short 10–15 min talks describing their specific research activities. Presentations emphasized their needs and experience with key aspects of pre-drilling, drilling, onboard sample handling, in-repository sample handling and long-term storage. Topics included sample frequency, contamination checks, core flow, geochemical measurements, cell enumeration, sample archives, data submission, staffing needs, education and collaborations with other scientific disciplines. Discussions that followed the presentations identified an apparent communication gap between the scientific drilling community and deep biosphere researchers that is inhibiting the progress of the entire community. The lack of communication was said to affect each stage of exploration from the pre-drilling planning stages through the drilling process to the post-drilling analysis. Misconceptions included the technical requirements for biological sampling, the frequency and targets for biological research, and sample preservation and storage. These issues are discussed below.

3 Enhance communications and expectations

Workshop participants suggested a three-level approach to improve the communication and expectation of biological research for upcoming drilling operations to help develop and implement a feasible set of standardized protocols for microbiological drilling, sample handling and long-term storage. Where possible, we took into account the diversity of drilling operations, i.e., “traditional” drilling, seabed drilling and long piston coring. While the expectations listed below are more specific to IODP, a similar level-based structure with program-specific expectation should be discussed and determined with these expectations acting as the catalyst for future discussion. The levels suggested are as follows.

3.1 Level 1: expeditions with few to no geomicrobiological components

Expectation: a technician trained in microbiology sampling will be on board. There will be low-frequency core sampling with no onboard contamination checks. Proposals listing this level for biology will not receive support from the biosphere community to improve rank when evaluated by the IODP proposal evaluation panel. Support will be provided to determine ways to enhance the biological components within the drilling plan and to demonstrate how these enhancements will help increase the scientific output of the expedition.

3.2 Level 2: expeditions with a modest geomicrobiological component

Expectation: at least one of the sailing scientists will be a microbiologist. A technician trained in microbiology sampling will also be on board. There will be more frequent core sampling with onboard contamination checks completed and limited supporting geochemistry compared to a Level 1 expedition. Proposals listed at this level will receive some support from the biosphere community to improve rank when evaluated by the IODP proposal evaluation panel. Support will be provided to determine ways to further enhance the biological components within the drilling plan and to demonstrate how these enhancements will help increase the scientific output of the expedition.

3.3 Level 3: expeditions with a significant or predominant geomicrobiological component

Expectation: two sailing scientists should be microbiologists. A technician trained in microbiology sampling will also be on board. There will be frequent core sampling with full onboard contamination checks, onboard cell counting, extended geochemical analysis and onboard CAS freezing facilities. For information on CAS freezing, please see Morono et al. (2015). Proposals listed at this level will receive full support from the biosphere community to improve rank when evaluated by the IODP proposal evaluation panel. Expedition advertisements and promotion within the biosphere community will ensure adequate pre-expedition planning, and onshore and offshore research, and post-expedition data and sample preservation will be made possible.

These levels are meant to promote proper communication of scientific expectations and requirements between expedition leaders and participants, an area that is currently plagued with misconceptions from both sides. Early communication during the proposal-writing phase will help guide sample requests and operational expectations of the chief scientists, biologists and drilling operators. The level approach was further refined through three subgroups organized based on an expedition planning and operation timeline. The groups were focused on predrilling and drilling, onboard sample processing and post-cruise legacy samples and data. Greater detail for these levels will be provided in the handbook being written by workshop participants. Details describing the handbook are provided below in Sect. 5.

4 Legal requirements for microbiological sampling within the economic exclusive zone (EEZ) through scientific drilling

During the workshop, we discussed possible legal requirement issues for microbiological samples regarding the Nagoya Protocol on Access and Benefit-Sharing (ABS, http://www.cbd.int/abs/). Briefly, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity (CBD) is an international agreement at the government level, which aims at sharing the benefits arising from the utilization of genetic resources in a fair and equitable way. The Nagoya Protocol, created for greater legal certainty and transparency for both providers and users of genetic resources, was enacted on 12 October 2014, with the support of 57 countries. The Nagoya Protocol specified obligations to support compliance with the domestic legislation or regulatory requirements of the contracting party providing genetic resources, and contractual obligations reflected in mutually agreed terms. The contracting parties of the Nagoya Protocol are to take measures to ensure genetic resources utilized within their jurisdiction have been accessed in accordance with prior informed consent (PIC), and that mutually agreed terms (MAT) have been established, as required by another contracting party.

The United Nations Convention on the Law of the Sea (UNCLOS) establishes a plan of sovereignty over parts of the seas. The resources of the seas within state jurisdiction covered by UNCLOS are then accessed and shared according to the procedure established by the CBD and the Nagoya Protocol. The interaction of UNCLOS and the CBD means that the access regime of the CBD extends to all genetic resources (both terrestrial and marine) within the coastal state's jurisdiction. In this regard, the legal regulation is highly relevant to the deep biosphere-related sampling through IODP and other academic activities in the economic exclusive zone (EEZ). For example, during an IODP drilling project in the EEZ of a certain country, the samples used for biology are considered genetic resources belonging to that country, and should be taken following the regulations of the domestic law through the PIC and MAT. The complicacy of the Nagoya Protocol is that not all the party countries have already established the regulations and systems. Moreover, implementation of the Nagoya Protol in national legal systems has led to very diverse regulations that are different in each country. This might make microbiological sampling with IODP difficult when the drilling sites are located within the EEZ of a nation. ICDP drilling operations are affected as well.

Given the situation, the workshop participants recognized that it is important to share the knowledge among the IODP community and discuss possible issues that should be addressed properly before the drilling expedition at the IODP implementation organization level. Other organizations will have similar difficulties with the Nagoya Protocol and should also establish a working protocol to remain in compliance while not interfering with the biological exploration of the subsurface.

5 DEEP BIO Handbook

By the end of the workshop, a full handbook for microbiological and proxy-based paleoclimate drilling operations was determined to be both necessary and possible. The Deep Earth Exploration for Paleoclimate and Biosphere Investigation and Observation (DEEP BIO) Handbook is meant to promote proper communication of scientific expectations and requirements between expedition leaders and participants, an area that is currently plagued with misconceptions from both sides. As a result of discussions during the workshop, participants and selected experts were asked to assist in the writing of the handbook's four main sections: (1) Pre-drilling preparations and planning; (2) On-site operations; (3) Post-drilling processing and storage; and (4) Future Development (Table 1). Opportunities for community involvement in the writing process are discussed below.

Workshop participants, organized in breakout groups, identified multiple key points within each handbook section to help describe the needs of the biosphere community and where the biosphere community should be more proactive and involved. The early stages of proposal writing and planning were seen as a key time point for increased input from

Table 1. Sections and topics to be included in the DEEP BIO Handbook.

Handbook section	Initial topics for discussion
Pre-drilling preparations and planning	Proposal writing involvement
	Sample request writing and expectation Procedure/methods/protocol preparations
On-site operations	Contamination check technology and application Personnel needs Efficient and sterile sampling procedure On-site analysis in support of biological objectives
Post-drilling processing and storage	Storage requirements to maximize sample viability Repository requests and sample availability
Future development	Technologies for drilling, sampling and storage On-site technique developments Advances in data management

the biosphere community. Early activity in the proposal writing process will promote the inclusion of specific biological objectives within the main science plan and help alleviate misconceptions about the operational demand of biological sampling. Thus, sample requests, as well as drilling procedures, methods and protocols, should be discussed among all proponents in order to include a biological perspective of the overall goals of the drilling project. To accomplish biological inclusion in the proposal writing stage, monitoring of submitted proposals, involvement on planning committees and communication within the biosphere community are required.

The section describing on-site operations will focus on personnel needs, quality assurance and quality control protocols including the use of contamination checks, standardizing sampling procedures and requirements to increase efficiency and reduce core disruption, and on-site analysis protocols to maximize post-drilling research potential. Discussions were stimulated by recent work by Lloyd et al. (2013) that illustrated how different molecular methods used in multiple laboratories produced inconsistent results and thus suggested standardizing protocols to help link data sets. A standardized, high-throughput cell counting method, presented by Yuki Morono (Fig. 1), will be included in the handbook as one of the recommendations for on-site analysis (Morono et al., 2013). Additional methods will be considered with the understanding that the handbook should be updated as technologies advance.

Post-drilling preservation of both samples and data will be detailed in the third section. This will include recommendations as to how these resources can be made more accessible to a broader community. Additional mechanisms for sample storage and data archiving will be examined. Shifts in the metabolically active microbial community structure have been previously observed in cores under standard IODP storage conditions, suggesting alterations of the physical and chemical characteristics (Mills et al., 2012b). The advanced preservation techniques and cryo-sampling procedures currently being used in the Kochi Core Repository DeepBIOS program led by Nan Xiao will described. Recommendations will be made to expand this program.

In the Future Development section, drilling technologies such as gel coring and large diameter side-wall coring will be

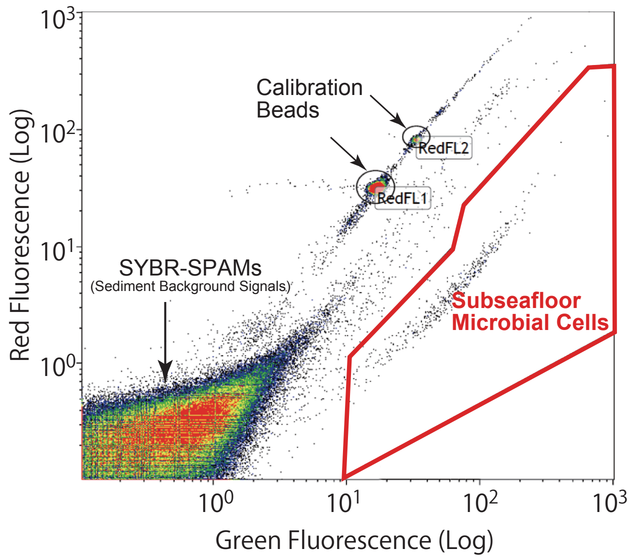

Figure 1. Standardization of cell counting techniques. The determination of cell abundance is a basic measurement common to most subsurface microbial community descriptions. An automated flow cytometer system can be used to determine cell abundances with high reproducibility and at a high sample rate (Morono et al., 2008). This method can be used repeatedly at multiple drill sites to reduce human errors and provide better connectivity between projects. (Figure is being used with permission from Yuki Morono; Morono et al., 2013.)

highlighted to increase community discussion on sampling needs. This section will be used to help build new initiatives and discussions. It is our goal that new innovations will help advance biosphere exploration beyond the current challenges with the understanding that more challenges will be realized. Techniques and technologies in this section may be moved to other sections as they become more widely used.

The handbook will be initially tested during IODP expedition planning, drilling and post-expedition operations to determine feasibility and then used to train technicians and scientists. Protocols and procedures specific to different ocean and terrestrial drilling platforms, as well as within the repositories, will be included. Community involvement is welcome during the writing of this handbook. If you would like to contribute and be involved, please contact Heath Mills at geobiolab@gmail.com. The handbook will be designed to accommodate regular updates so that it may continue to guide subsurface exploration in the future.

The workshop successfully brought together an energetic and knowledgeable group that worked efficiently toward our goal of improving subsurface biosphere exploration. The key focal point discussed for moving forward was improving communication within the drilling community to improve overall understanding of the requirements and expectations for biosphere exploration. Deliverables from this workshop include an EOS newsletter article (Mills et al., 2014), this paper and a handbook to be written by workshop participants with community input.

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ECORD School of Rock 2015

Giving continuity to the success of the first ECORD School of Rock (SOR), held in France in 2014, this year's event took place in Portugal from 8 to 10 July. The workshop entitled "Investigar e estudar a Terra sob o fundo do mar" was held at the Loulé Secondary School (ESL) and was attended by 35 teachers from all over Portugal. Its main goal was to educate participants about the International Ocean Discovery Program (IODP), scientific ocean drilling and Earth science through the interaction with expedition scientists and former teachers at sea. To achieve that objective, the 3-day-long workshop included presentations, given by scientists, and practical hands-on sessions, developed and tested by scientists and educators who sailed on board the JOIDES Resolution (see http://ecord-sor2015.blogspot.pt/?view=snapshot). The ECORD SOR 2015 participants went home with a vast amount of information and a new appreciation for how world-class, cutting edge science is conducted. In future they will be able to use what they have learned to enhance the teaching of science in their schools, to share ideas with other teachers, and to encourage their students to explore a wide variety of opportunities in the world of scientific exploration.

Helder Pereira, education officer during IODP Exp. 339 and science teacher at Loulé Secondary School, Portugal.

ICDP training courses on lake drilling and project management

Two International Continental Scientific Drilling Program (ICDP) training courses were held in Fall 2015. The ICDP Training Course on Lacustrine Sediment Drilling at Lake Ohrid and Lake Prespa, Macedonia, from 14 to 16 September was attended by 20 scientists from 15 countries who followed lectures and performed practical exercises related to scientific drilling of lacustrine sediments. Practical exercises included interpretation of data from seismic surveys to define the best possible drilling locations, drill core opening, and core handling. Principal investigators (PIs) from successfully completed ICDP lake drilling projects (SCOPSCO, Towuti) provided valuable insights into the planning and execution of lake drilling campaigns. Other lectures covered topics such as downhole logging, pre-site studies, on-site sample handling, storage and analysis, data management, funding and support by the ICDP, and outreach. Among the highlights of the training course were the visits to the UWITEC barge to see a small piston coring system in operation and to an airgun boat for seismic surveys, both at Lake Prespa.

A total of 22 PIs, project managers and leading scientists of upcoming continental scientific drilling projects were invited to the ICDP Training Course on Planning, Management and Execution of Continental Scientific Drilling Projects, from 19 to 21 October 2015, at the Geo-Zentrum KTB. This training course touched upon relevant aspects for managing a scientific drilling project, including proposal writing and multi-source fundraising, drilling engineering basics, HSSE (health, safety, security and environment), on-site management, sample handling and curation, downhole logging planning and execution, and outreach.

USSSP office at the Lamont-Doherty Earth Observatory

In March of 2015, the Lamont-Doherty Earth Observatory (LDEO) of Columbia University entered into a 5-year cooperative agreement with the U.S. National Science Foundation to manage the U.S. Science Support Program (USSSP) associated with the International Ocean Discovery Program (IODP). The USSSP is responsible for providing financial and managerial support for many components of the U.S. IODP effort, including program planning and development (through funding of workshops), expedition participation (by providing a salary for sailing scientists), and pre-drilling activities, among numerous other program elements. The new USSSP office at LDEO will also manage a diverse portfolio of education and outreach activities, including a new collaboration with the American Museum of Natural History in New York City.

The USSSP is advised by the 10-member U.S. Advisory Committee for Scientific Ocean Drilling (USAC), now under the leadership of Chair Beth Christensen of Adelphi University. Dr. Christensen has participated on numerous ODP (Ocean Drilling Program) and IODP expeditions and pursues research on climate and sea level change, paleoceanography, and reef sediments. USAC provides advisory assistance to the USSSP with workshop and pre-drilling activity reviews, expedition staffing nominations, panel membership selection, graduate student fellowship awards, and other activities.

The website for the new U.S. Science Support Program can be found at usoceandiscovery.org.

Australian membership of IODP now funded until 2020

The Australian Minister for Education and Training, the Honourable Simon Birmingham, recently announced that the Australian Research Council has granted funding for another 5 years to an Australian IODP consortium. With additional funding from our 16 Australian scientific partners we have nearly AUD 2.9 million p.a., and we expect further funding from four New Zealand partners so that ANZIC (the Australian and New Zealand IODP Consortium) can continue as an important Southern Hemisphere partner. The present exchange rate would enable us to continue at our present satisfactory level within the IODP.

This grant is a credit to all those who were directly involved in the funding bid and indeed to all those who have been involved in our IODP activities. Of course, our past performance has made this success possible. Australia and New Zealand are very significant scientific partners in the IODP, as nicely illustrated by the number of ANZIC-led expeditions planned for our region in the next few years. The USA, Europe and Japan make the IODP possible by providing all the logistical and storage capabilities, and we are extremely grateful to them.

Over the next 3 years, Australasia’s offshore jurisdiction and neighbouring regions will be a major focus of IODP activity. Five regional IODP expeditions are scheduled for the period from 2015 to 2018 and four more may be scheduled before 2020. At this moment, four JOIDES Resolution expeditions and one alternative platform expedition will be in our general region. The JOIDES Resolution successfully drilled the Indonesian Throughflow Expedition 356 off northwestern Australia in August and September 2015, before heading westward for an extensive Indian Ocean campaign. The two Australian port calls were an opportunity to share cutting edge science with pupils from local schools and scientists from universities and the petroleum industry. We had the pleasure of hosting the Assistant Minister for Science, the Honourable Karen Andrews, in Darwin, and she expressed great interest in the JOIDES Resolution and the IODP science program.

Stephen Gallagher (Expedition 356 Co-chief Scientist), Brad Clement (JOIDES Resolution Science Director), Australian Assistant Minister for Science Karen Andrews, and Neville Exon (ANZIC Program Scientist) talking during the Darwin port call of the JOIDES Resolution.

Five Australians took part in Expedition 356, which drilled six holes – south to north from 28°S to 18°S. It was designed to investigate the last 5 million years of Earth's history, including changes in the flow of the huge ocean currents south and west of the Indonesian straits, as sea levels rose and fell by about 140m; associated changes in Australia’s climate; and unusual tectonic events. About 5000m of sediments and sedimentary rocks were recovered and described and will be subject to extensive further scientific examination. The main results will be published in leading science journals.

Expedition 369 off southwestern Australia, dealing with southern Cretaceous climate and tectonics and scheduled for late 2017, will be the next JOIDES Resolution expedition in purely Australian waters. It is designed to investigate a broad suite of questions: the rise and collapse the Cretaceous hothouse, oceanic anoxic events, Cretaceous deep and intermediate water circulation, Cenozoic paleoceanography, basement composition and depositional history, and the Gondwanan breakup.

In early 2016 we intend to publish a major review detailing all ANZIC activities in the first phase of the IODP, in which we were involved from 2008 to 2013.

Neville Exon, ANZIC Program Scientist

Schedules

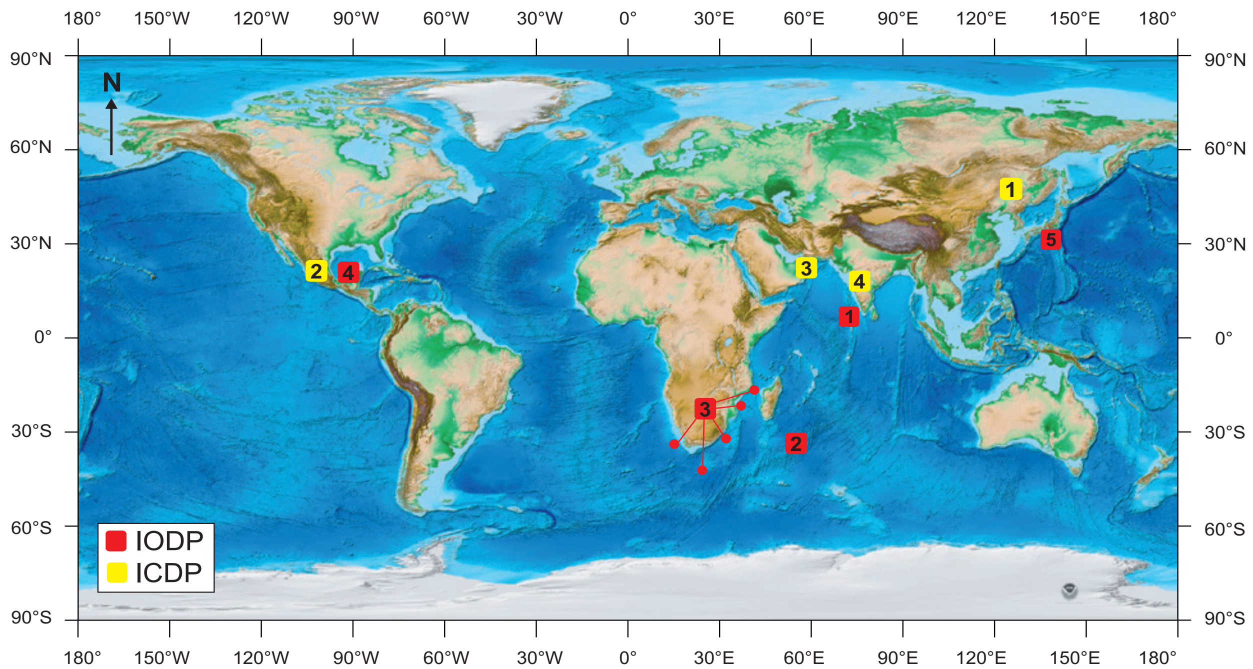
IODP – Expedition schedule http://www.iodp.org/expeditions/

USIO operations	Platform	Dates	Port of origin
1 359 Maldives Monsoon	JOIDES Resolution	30 Sep–30 Nov 2015	Darwin, Colombo
2 360 Indian Ridge Moho	JOIDES Resolution	30 Nov–30 Jan 2016	Colombo / Port Louis, Mauritius
3 361 Southern African Climates and Agulhas Current Density Profile	JOIDES Resolution	30 Jan–31 Mar 2016	Port Louis / Capetown
ECORD operations	**Platform**	**Dates**	**Port of origin**
4 364 Chixulub Impact Crater (jointly with ICDP)	MSP	Apr–May 2016	TBD
CDEX operations	**Platform**	**Dates**	**Port of origin**
5 365 NanTroSEIZE Shallow Megasplay LTBMS	Chikyu	26 Mar–27 Apr 2016	TBD

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

ICDP project	Drilling dates	Location
1 Songliao Basin	Apr 2014–Dec 2016	Songliao Basin, China
2 MexiDrill	Dec 2015–Feb 2016	Chalco Basin, Mexico
3 Oman	Feb–May 2016	Oman
4 Koyna	Jan–Nov 2015	Koyna, India

Locations



Topographic/Bathymetric world map with courtesy from NOAA (Amante, C. and B.W. Eakins, 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M).