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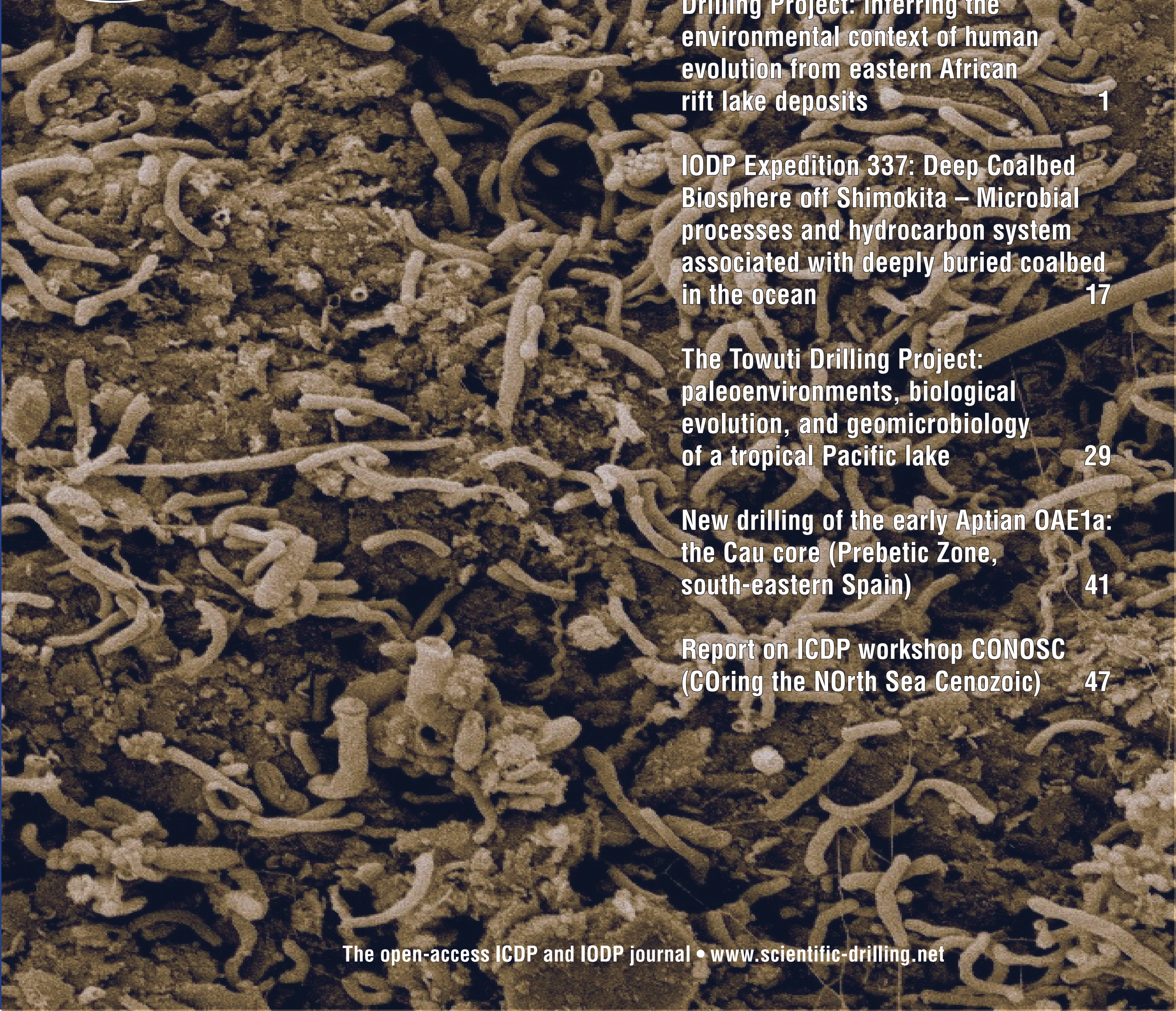
Reports on Deep Earth Sampling and Monitoring



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Editorial preface

Dear reader,

Where and under what conditions is our planet habitable for life at depth? And how and why do changes in the environment that impact the evolution of life occur? And what about our own species? What conditions and what changes of the planet Earth favoured the evolution of the first hominins strolling and dwelling in Africa? These key questions about life and habitability are the focus of this issue of your journal Scientific Drilling.

For the first time the riser drillship *Chikyu* has been deployed by the International Ocean Discovery Program (IODP) in Expedition 337 to study the subseafloor microbiology. The forearc basin formed by the subduction of the Pacific Plate off the Shimokita Peninsula, Japan, was drilled to sample the deep microbial biosphere and a series of 2 km deep subseafloor coalbeds and to explore the limits of life in the deepest horizons ever probed by scientific ocean drilling (see pages 17 to 28).

Further south, in central Indonesia on the island Sulawesi, Lake Towuti hosts a unique endemic fauna and unusual microbes living in metal-rich sediments. The Towuti Drilling Project in the International Continental Scientific Drilling Program, ICDP, has recovered more than 1000 m of these sediments that hold clues to the changing environment in the West Pacific Warm Pool (pages 29 to 40).

The Hominin Sites and Paleolakes Drilling Project (HSPDP) of the ICDP recovered cores from lakebeds in the proximity of five important early human fossil sites in Ethiopia and Kenya (pages 1 to 16). The large international HSPDP consortium is using the samples to better understand the environmental and climatic context of human evolution in the past 4 million years.

A view further back in Earth's history to understand present changes is provided also by a progress report on the Cretaceous Oceanic Anoxic Event (OAE1a) drilled in the Prebetic Zone of Spain (pages 41 to 46) and by a workshop report on the CONOSC (COring the NOrth Sea Cenozoic) project that aims at the continuous 65-million-year record in the north-western European marginal sea basin (pages 47 to 51).

We hope you will enjoy this exciting and informative read,

Your editors,
Ulrich Harms, Thomas Wiersberg, Jan Behrmann, Will Sager, 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 programmes 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.

Editorial board

Additional information

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Cover figures:
A scanning electron micrograph for deep microbes cultivated from 2 km deep lignite coal samples. Photo credit: Hiroyuki Imachi, JAMSTEC
Insert 1: The drilling vessel *Chikyu* at Site C0020 during Expedition 337. Photo credit: JAMSTEC
Insert 2: 2 km deep coal core sample on the *Chikyu*. Photo credit: Luc Riolon

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Scientific Drilling
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The Hominin Sites and Paleolakes Drilling Project: inferring the environmental context of human evolution from eastern African rift lake deposits

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Abstract. The role that climate and environmental history may have played in influencing human evolution has been the focus of considerable interest and controversy among paleoanthropologists for decades. Prior attempts to understand the environmental history side of this equation have centered around the study of outcrop sediments and fossils adjacent to where fossil hominins (ancestors or close relatives of modern humans) are found, or from the study of deep sea drill cores. However, outcrop sediments are often highly weathered and thus are unsuitable for some types of paleoclimatic records, and deep sea core records come from long distances away from the actual fossil and stone tool remains. The Hominin Sites and Paleolakes Drilling Project (HSPDP) was developed to address these issues. The project has focused its efforts on the eastern African Rift Valley, where much of the evidence for early hominins has been recovered. We have collected about 2 km of sediment drill core from six basins in Kenya and Ethiopia, in lake deposits immediately adjacent to important fossil hominin and archaeological sites. Collectively these cores cover in time many of the key transitions and critical intervals in human evolutionary history over the last 4 Ma, such as the earliest stone tools, the origin of our own genus Homo, and the earliest anatomically modern *Homo sapiens*. Here we document the initial field, physical property, and core description results of the 2012–2014 HSPDP coring campaign.

1 Introduction

The possibility that human evolution has been strongly influenced by changes in the Earth's environmental history, and in particular, its climate history, has been at the forefront of paleoanthropological research for the last 25 years. Few subjects captivate the public interest as much as human evolution and climate change. Today there are compelling scientific and societal needs to clarify the role of climate history in the evolution of our own species, *Homo sapiens*, and the evolution and extinction of our close relatives (collectively referred to as hominins). Much of the debate about human origins, from the time of the split between the hominins and the ancestors of the African great apes, about 6 Ma, has centered around the fossil record of Africa. This is where the vast majority of hominin fossils > 1 Ma in age have been discovered, and where many important evolutionary transitions in our lineage apparently occurred, such as bipedalism, the use and increasing complexity of stone tools, and increased brain size. Within the African continent, the eastern Rift Valley has been a particularly prominent region for understanding human origins, as its deep tectonic basins have provided a depositional context for the accumulation of fossil hominins and other organisms, as well as a sedimentary record allowing us to both date the fossils and put them in a paleoenvironmental context.

Numerous hypotheses linking both global and regional African climate to hominin evolutionary history have been proposed. Vrba (1985, 1988, 1995) hypothesized that Neogene mammalian (including hominin) evolution and extinction occurred in coordinated and relatively rapid turnover pulses triggered by major, directional, global environmental changes, such as the intensification of Northern Hemisphere glaciation. However, mammalian records indicate that the impact of these global mechanisms varied at local and regional levels (Alemseged, 2003; Bobe and Behrensmeyer, 2004; Bobe et al., 2007; Reed, 2008). Other major advances in understanding eastern African paleoclimate (e.g., deMenocal, 1995, 2004; Trauth et al., 2005; Scholz et al., 2007, 2011) have spurred the development of explanatory, dynamic paleoclimate models, as well as alternative models linking paleoclimate and human evolution. Potts (1996;

Potts and Faith, 2015) proposed that it is the variability in climate (especially at orbital forcing timescales) as opposed to simply its directional history (e.g., drying trends) that has driven large-scale evolutionary changes and technological innovations among the hominins. Unfortunately, because local outcrop paleorecords are either incomplete or discontinuous, no consensus yet exists on the factors that interacted to control African climate and ecosystem dynamics during the Plio-Pleistocene or how they affected hominin or other mammalian evolution.

On long timescales ($>10^6$ years), there is debate on the timing and importance of eastern African uplift and changes in oceanic circulation as causes of climate change, and especially increasing aridity, the development of extensive grassland savanna, and their influence on the mammalian fauna (Cane and Molnar, 2001; Molnar and Cane, 2007; Sepulchre et al., 2006; Wichura et al., 2010; Cerling et al., 2011; Federov et al., 2013; Maslin et al., 2014). On intermediate timescales (10^4–10^6 years), there is controversy regarding the relative importance of high-latitude glacial cycles, Walker circulation intensification, and annual- to decadal-scale variability in atmospheric pressure and sea surface temperatures such as El Niño–Southern Oscillation and the Indian Ocean Dipole (ENSO/IOD) for regional aridity, lake expansions, and seasonality (deMenocal, 2004; Trauth et al., 2009), all of which could have influenced the course of evolution in the lake-rich Rift Valley. On Milankovitch (~ 100, 40, and 20 kyr) and shorter (10^1–10^4 years) timescales, there is debate about the role of orbital forcing and high-latitude glacial to millennial-scale events in driving wet–dry cycles that increased environmental pressures on African ecosystems (e.g., Larasoaña et al., 2003; Kingston et al., 2007; Scholz et al., 2007; Campisano and Feibel, 2007; Trauth et al., 2009, 2015; Armitage et al., 2011; Blome et al., 2012), and how these might have influenced resource acquisition (Reed and Rector, 2007) and other ecological parameters affecting hominins. Assessing these hypotheses is complicated by the need to understand the role of biotic drivers of adaptation, such as competition and predation. One fundamental question is whether any of the Earth system drivers can be characterized with sufficient precision to identify drivers of diversification and extinction among our close relatives and ancestors and to enable correlation with hominin evolution.

Past attempts to test hypotheses that implicate climate as a major driver of human evolution have often foundered on a fundamental mismatch of spatial and temporal scales, casting highly temporally resolved, but globally or continentally spatially averaged records of climate change against less temporally resolved but basin-scale records of faunal change and/or hominin evolution. This approach cannot yield a realistic understanding of potential linkages between environmental and biotic change, because it ignores basin-scale environmental dynamics relating to changes in regional climate, that is, local tectonics and geomorphology, which could also be drivers of mammalian population dynamics. For example, Behrensmeyer et al. (1997) tested Vrba's turnover pulse hypothesis by investigating whether such a pulse occurred in changing mammal communities at 2.8 Ma in the Turkana Basin of northern Kenya, a region with a rich and highly continuous fossil record. They found that species patterns in the Turkana Basin did not follow this global model, and that species turnovers were more prolonged responses to climate change associated with both drier and more variable climatic conditions. Tectonic forcing (Bailey et al., 2011) and extreme environmental perturbations, such as megadroughts (Cohen et al., 2007; Scholz et al., 2007), have also been suggested as potential drivers of early modern human population fragmentation, genetic differentiation, range expansion events, and adaptation (Mellars, 2006). The implications of millennial-scale or even shorter events for early hominin evolution have scarcely been explored as they are poorly resolved in offshore marine records. However, such events were clearly linked to major demographic and population-level changes during the Holocene in Africa (e.g., Kuper and Kröpelin, 2006).

Current hypotheses remain difficult to test and there has been an acute need to develop new perspectives and data on the links between global- and basin-scale environmental change, and to relate these specific changes to ecological factors that influenced hominin evolution. The Hominin Sites and Paleolakes Drilling Project (HSPDP) was designed to improve understanding of the implications of ecosystem change for hominins in two ways: (1) to provide millennial-scale environmental data at key time periods that correspond to morphological and cultural changes or other perceptible evolutionary events in hominin and other mammalian lineages near locations where hominin fossils have been found, and (2) to compare these data across basins, encompassing multiple paleoanthropological localities, to document local versus regional effects of ecosystem change, and responses to global-scale changes. For the specific case of hominin and large mammal evolution in Africa, in order for a paleoenvironmental record to be useful for improving our understanding of the connection between evolution and climate, it must meet two conditions.

1. There must be a highly resolved paleorecord to examine environmental change at any temporal scale that could realistically serve as an evolutionary or ecological trigger. This would range from annual records of seasonality preserved in archives such as annual lake deposits, pollen records of plants responsive to variable seasonality, lipid markers of temperature, etc. to geochemical or sedimentological records of phenomena such as major uplift or paleoceanographic events, which might operate on much longer (e.g., $>10^6$ years) timescales.

2. A record of faunal change from the same localities that is sufficiently detailed to investigate responses to environmental change within particular clades, ecological guilds, or mammal communities.

The HSPDP was developed by an international team of over 100 scientists from 11 countries to address these issues. Its goal was the collection and analysis of high-resolution paleoenvironmental records from paleo-lake drill cores near the depocenters of lacustrine basins of significant paleoanthropological importance in eastern Africa, each of which meets these conditions. As discontinuously exposed outcrops have shown these lakebeds to be commonly laminated (e.g., Wilson et al., 2014) with bedding characteristics often similar to demonstrably annual varves documented in modern African rift lakes (Pilskaln and Johnson, 1991; Cohen et al., 2006) and deposited at high sedimentation rates, their records fulfill the first criterion. The second criterion is fulfilled as each of the drill sites lies in close proximity to rich and diverse fossil vertebrate and archaeological sites, with sediments of the same age, and which collectively span some of the most critical intervals of hominin evolutionary history (e.g., earliest *Homo*, earliest stone tools, origin of Acheulian and Middle Stone Age technologies, earliest modern *H. sapiens*), and where new, important fossils and artifacts are still being recovered. Thus, the integration and direct comparison of basin-scale records of environmental change from cores with the record of faunal and cultural change from outcrops affords us the opportunity to test existing hypotheses of Earth system drivers of evolution at different temporal and spatial scales.

2 Drilling target areas

A series of workshops held in the mid–late 2000s better defined the specific goals of the HSPDP and specific selection criteria for ideal drilling locations (Cohen and Umer, 2009; Cohen et al., 2009). The drilling areas (Table 1 and Fig. 1) were decided through a lengthy and interactive process between the principal ICDP project proponents. Numerous hominin fossil and archaeological sites in proximity to lake deposits in eastern Africa were considered as potential drilling targets, and ultimately the decision on which sites to pursue was determined by a combination of the scientific criteria mentioned above, along with practical, logistical considerations, such as site access for a truck-mounted drill rig and probable costs. The sites discussed below were part of the original HSPDP operational plan. The Olorgesailie (Koora Plain) site was ultimately funded separately from the remaining ICDP-supported sites.

2.1 The Northern Awash drilling area, Ethiopia

The Northern Awash basin provides one of the densest accumulations of early hominin fossils (Johanson et al., 1982; Kimbel et al., 2004; Alemseged et al., 2006), as well as rich mammalian faunal and floral records (Bonnefille et al., 2004; Reed, 2008; Geraads et al., 2012). Its lakebeds provide a potential record of the local environmental response to the onset of high-amplitude climate oscillations and increased aridity in eastern Africa at ∼ 3.15 Ma as well as the response to Milankovitch cycles prior to the onset of high-latitude glaciation (∼ 2.7 Ma) as documented in the marine core record (Campisano and Feibel, 2007). This site provides a backdrop against which ∼ 400 kyr of the evolutionary history of *Australopithecus afarensis* (e.g., "Lucy") and associated fauna and the earliest use of stone tools (McPherron et al., 2010) will be interpreted.

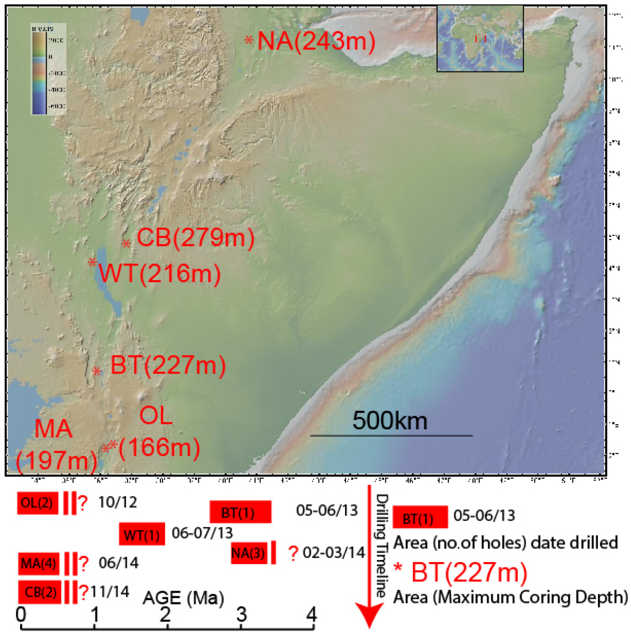

Figure 1. Map of eastern Africa showing locations of the HSPDP drilling areas; maximum coring depth for the deepest borehole in red on the map (the BT(227 m) example indicates the maximum depth, 227 m, that was reached at the BT site). The timeline below the map shows the number of cored boreholes, drilling dates, and approximate time intervals covered by the drill cores from each area. From north to south: NA: Northern Awash; CB: Chew Bahir; WT: West Turkana; BT: Baringo Tugen Hills; OL: Olorgesailie/Koora Plain; and MA: Lake Magadi. Base map generated from GeoMapApp©.

2.2 The Baringo Basin/Tugen Hills drilling area, Kenya

This area of the central Kenyan Rift Valley comprises the most complete late Neogene section known from the African rift (Chapman and Brook, 1978). The stratigraphic interval of the Chemeron Formation targeted here (3.3–2.6 Ma) contains ∼ 100 fossil vertebrate localities, including three hominin sites, providing an opportunity to explore the nature of environmental change associated with shifting insolation patterns (for example, documenting the lacustrine response to changing precipitation patterns at precessional, millennial, and perhaps even shorter timescales; e.g., Kingston et al., 2007; Wilson et al., 2014) and to assess specific terrestrial community responses to pervasive, short-term climatic

Table 1. Borehole site information for the HSPDP. DA: drilling area; age: approximate age range of borehole sediments; NA: Northern Awash, Ethiopia; BTB: Baringo/Tugen Hills, Kenya; WTK: West Turkana, Kenya; SK: southern Kenya; KO: Koora Plain/Olorgesailie; MAG: Lake Magadi; CHB: Chew Bahir, Ethiopia; ID: borehole identification number; SD: spud date; LAT: latitude N (−: S); LONG.: longitude E; BE: borehole surface elevation in meters above sea level; BI: borehole inclination in degrees off vertical; BT: borehole top depth in meters to top of cored interval from surface; DL: drilled length in meters; CL: cored length in meters; CR: total core recovered in meters; CR: percentage core recovery; LOG: downhole logging type; NG: natural gamma (U, Th, K); MS: magnetic susceptibility; R: resistivity; T: temperature. For MAG14-2A, MS was collected from 4 to 14 m and 82 to 197 m only, R from 4.5 to 12.5 m and 82.5 to 139 m, 143 to 161 m and 165 to 197 m only, and MS from 82 to 197 m only. For OLO12-1A the hole was reverse-circulation drilled down to 27 m with cuttings bagged from 0 to 27 m. For OLO12-2A, borehole was reamed to find bedrock depth (encountered at 159 m). No coring attempted.

Drilling area (age)	ID	SD	LAT.	LONG.	BE	BI	BT	DL	CL	CR	CR%	LOG
NA (Late Pliocene)												
	HSPDP-NAO14-1A	23/2/2014	11.315	40.7369	520	15	1.84	4.84	4.84	2.6	53.7	None
	HSPDP-NAO14-1B	23/2/2014	11.315	40.7369	520	13	1.29	187.4	187	205.4	110	None
	HSPDP-NAO14-1C	28/2/2014	11.315	40.737	521	13	0	3	3	2.67	88.8	None
	HSPDP-NAO14-1D	1/3/2014	11.315	40.737	521	14	0	168.4	167	181.9	109	None
	HSPDP-NAO14-1E	4/3/2014	11.315	40.7649	521	13	172.7	0	0	0	0	None
	HSPDP-NAW14-1A	11/3/2014	11.325	40.7649	495	12	0	244.5	245	254.6	104	None
BTB (Late Pliocene–Early Pleistocene)												
	HSPDP-BTB13-1A	1/6/2013	0.5546	35.9375	1158	0	5.25	227.9	223	210	94.3	NG, MS, R, T
WTK (Early Pleistocene)												
	HSPDP-WTK13-1A	22/6/2013	4.1097	35.8718	404	10	0.55	215.8	215	202.6	94.1	NG, T
SK (Middle Pleistocene–Holocene)												
OL												
	ODP-OLO12-1A	5/9/2012	−1.791	36.4011	862	0	27	166.1	139	130.8	94	None
	ODP-OLO12-2A	17/9/2012	−1.7887	36.3968	862	0		159	0	0	0	None
	ODP-OLO12-3A	21/9/2012	−1.7887	36.4085	852	0	50	116.3	66.3	66.73	101	None
MAG												
	HSPDP-MAG14-1A	11/6/2014	−1.8805	36.2717	607	0	3.02	128.5	126	74.51	59.2	None
	HSPDP-MAG14-1B	23/6/2014	−1.8806	36.2717	607	0	119.64	125.7	6.1	2.87	47	None
	HSPDP-MAG14-1C	25/06/2014	−1.8806	36.2717	607	0	3.44	136.6	26.5	16.84	63.6	None
	HSPDP-MAG14-2A	29/06/2014	−1.8516	36.2794	607	0	3	197.4	194	107.7	55.4	NG, MS, R, MS
CB (Middle–Late Pleistocene)												
	HSPDP-CHB14-1A	18/03/14	4.4225	36.5109	500	0	0	41.5	39.1	39.05	94	None
	HSPDP-CHB14-2A	6/11/2014	4.7612	36.7668	500	0	0.49	278.6	284	245.4	86.6	None
	HSPDP-CHB14-2B	19/11/2014	4.7613	36.767	500	0	0.28	266.4	266	240.9	90.5	None
Totals								2668	2192	1985	90.6	

change through the interval of Northern Hemisphere glacial intensification. At this time in eastern Africa we also observe the diversification of *Paranthropus* (a group of hominins with robust cranial features and large teeth for a strong bite force) and our own genus Homo, as well as the earliest evidence for stone tool-making in nearby West Turkana (Harmand et al., 2015).

2.3 The West Turkana drilling area, Kenya

This area targets the Early Pleistocene lakebeds of Turkana, Kenya, that were deposited during a phase of overall increasing continental aridity punctuated by major lake-level fluctuations, which appear to reflect insolation-forced climate cycles (Lepre et al., 2007; Joordens et al., 2011). The extensive outcrops of the Turkana Basin have been well characterized geologically (Feibel, 2011) and have provided an unparalleled tephrostratigraphic framework (Brown et al., 2006) associated with precise chronostratigraphic controls (McDougall et al., 2012). This borehole is in direct proximity to the rich fossil record of the Turkana Basin, including ∼ 500 hominin fossils and more than 100 archaeological sites (Harris et al., 1988; Roche et al., 2004). The hominins include significant specimens, such as the earliest/most complete specimens of *H. rudolfensis* and *H. erectus*, early members of our own genus. The time window targeted here (∼ 1.9–1.4 Ma) also includes the earliest evidence of Acheulean (e.g., large hand axes) stone tool technology (Lepre et al., 2011) and the interval when hominins first expanded their range outside of Africa. The core record will allow us to explore whether (and which) climate drivers caused the expansion of grassland habitats in the early Pleistocene in this region, what climatic conditions/changes were associated with the first appearance of early Homo (*H. habilis/rudolfensis*) and the emergence of *H. erectus*, and what were the temporal links between climate change, the episode of major faunal turnover (i.e., the near-wholesale replacement of one set of species by another), grassland expansion, and the appearance of *H. erectus*, all occurring shortly after 2 Ma in the Turkana Basin.

2.4 The southern Kenya (Olorgesailie and Lake Magadi) drilling areas

These drill sites comprise contemporaneous Early Pleistocene to modern records from two adjacent (but hydrologically distinct) basins. Drill cores from these localities in the southern Kenya rift may provide a regional equatorial paleoclimate history of the major Middle–Late Pleistocene climate transitions, which is otherwise recorded from this region in only discontinuous records. Drilling on the Koora Plain will allow us to examine deposits immediately adjacent to the Olorgesailie depositional basin, one of the richest, best-calibrated Early–Late Pleistocene archeological localities in Africa, with abundant Acheulean and Middle Stone Age (MSA) sites (and documenting the transition between these important technological phases of human prehistory), diverse fauna, a detailed paleoenvironmental record, and abundant tephras (e.g., Potts et al., 1999; Sikes et al., 1999; Behrensmeyer et al., 2002; Owen et al., 2008). Prior research here has fueled hypotheses and debates about climate–evolution relationships (e.g., Owen et al., 2009a, b; Trauth and Maslin, 2009).

Nearby Lake Magadi ($\sim$ 20 km from the Koora Plain drill site) is located in the axis of the southern Kenya Rift and is a regional sump for water and sediments. The present lake, a saline/alkaline pan, is the successor to a series of paleolakes that have occupied the basin since the Early Pleistocene. Previous outcrop and drill core records (none of which survive) established the volcanic and sediment stratigraphy and their linkage to basin hydrology (Baker, 1958; Surdam and Eugster, 1976; Crossley, 1979; Eugster, 1980; Jones et al., 1977). The close proximity of both basins will provide us with an opportunity to tease out climatic from tectonic/groundwater controls on their respective environmental histories, contributing to HSPDP Objective 2 – the evaluation of how global climate changes were experienced locally within key hominin locales.

2.5 The Chew Bahir drilling area, Ethiopia

This area comprises Middle–Late Pleistocene lakebeds in a region between the Ethiopian and Omo-Turkana rifts, each of which has a highly distinctive Quaternary biogeographic history (Suwa et al., 2003) and border presumed habitat refuge areas during times of climatic stress (Foerster et al., 2015). Chew Bahir is an ephemeral playa today, but in the past has held a large lake (Foerster et al., 2012). Our records from Chew Bahir, presumed to cover at least the last 700 kyr, will also provide a regional-scale environmental context for the earliest anatomically modern *H. sapiens* fossils recovered at $\sim$ 200 ka in the nearby (90 km away) Omo River valley (Day, 1969; McDougall et al., 2005; Brown et al., 2006). When coupled with the other Early Pleistocene–recent HSPDP records from Olorgesailie and Magadi and previously collected drill core records from Lake Malawi and elsewhere in the region, the details of regional environmental heterogeneity in eastern Africa through the extreme climatic fluctuations of the Quaternary may be explored (e.g., Blome et al., 2012).

3 Pre-drilling site surveys

Between 2008 and 2012 subsurface and outcrop site survey data were collected in a series of campaigns from all of the drill sites to determine optimal locations for the various boreholes. The objective was to minimize the likelihood of encountering subsurface faults or associated deformation and to maximize stratigraphic resolution. Seismic data were acquired by our group at the Afar, West Turkana and Olorgesailie areas. Additionally, legacy industry seismic data were obtained from an old (1970s) AMOCO survey at West Turkana and very recently acquired survey data from Tullow Oil at the Chew Bahir area. Gravity and magnetic surveys were also conducted by our team at the Magadi and Olorgesailie areas. Prior boreholes drilled by the US Geological Survey in the late 1960s at Lake Magadi provided additional information for that area. Siting at the Baringo Basin/Tugen Hills was based on known outcrop exposures immediately adjacent to the drill site.

4 Drilling and logging operations (Figs. 2 and 3)

Drilling of the HSPDP sites took place over an approximately 2-year period between September 2012 and December 2014. Local drilling contractors, Drilling and Prospecting International for Kenya areas, Addis GeoSystems for the Chew Bahir pilot hole, and Geosearch (now Orezone Drilling) for all other holes in Ethiopia, provided truck-mounted standard wireline diamond coring drill rigs and crews. DOSECC Exploration Services (DES) provided drilling operations oversight, local supervision and specialized lake tools, bits, and other drilling supply procurement for items that were not locally available. Boreholes were drilled using a combination of H (96.3 mm diameter hole, 61.1 mm diameter core), P (122.6 mm hole, 66 mm core), and minor N (75.7 mm hole, 47.6 mm core, at Awash) diameter drill string and a variety of coring tools depending on the highly variable lithologic conditions encountered during drilling. P was employed when using the specialized lake coring tools in unconsolidated sediments. These included the hydraulic piston corer, the “extended nose” non-rotating corer, “alien” rotating corer, all using standard IODP butyrate core liners. Boreholes were

Figure 2. HSPDP drilling operations: **(a)** Oso Isi drill site (NAO14) in the Northern Awash area, northern Ethiopia (photo C. Campisano); **(b)** West Turkana (WTK13) drill site, with Lake Turkana and North Island in the background (photo A. Cohen); **(c)** West Turkana drill site (photo A. Noren); **(d)** Koora Plain/Olorgesailie (OLO12-1A drill site with Mt. Olorgesailie in the background (photo R. Dommain).

Figure 3. HSPDP drilling operations: **(a)** Lake Magadi drill site (MAG14) in the southern Kenya Rift Valley. Crystalline trona on the dry Magadi pan visible in the foreground (photo A. Cohen); **(b)** Chew Bahir drill site (CHB14) in the southern Ethiopian Rift Valley, Hammar Range in the background (photo A. Cohen); **(c)** HSPDP presentation to the local community group by National Museums of Kenya personnel at the Tugen Hills drill site (photo courtesy of National Museums of Kenya); **(d)** filmmaker Doug Prose of Earth Images Foundation filming tephra outcrops in the Omo River Valley, near the Chew Bahir drill site (photo A. Cohen).

oriented at 10–15° off the vertical at the Northern Awash and West Turkana sites to facilitate the interpretation of paleomagnetic data sets. At the Tugen Hills site, the existing $\sim 20°$ dip of sediments at the borehole site allowed us to drill vertically. At the three remaining sites (Magadi, Olorgesailie, and Chew Bahir) the presence of unconsolidated sediments made drilling at a non-vertical angle impractical, because the risk of cave-ins and losing hole integrity was deemed to outweigh the advantages for the paleomagnetic data interpretation. A Reflex ACT III orientation device was deployed with each drive at the West Turkana and Northern Awash sites to determine azimuthal data on non-vertical boreholes. Geophysical down-hole logging data were collected by ICDP's Operational Support Group for natural gamma, magnetic susceptibility (MS), resistivity, borehole temperature and azimuthal direction at three of the Kenyan sites (Tugen Hills/Baringo, West Turkana and Lake Magadi). Logging was limited at the West Turkana borehole because of lost casing remaining in the hole at the time of logging. No down-hole logging was conducted at the remaining sites due to unforeseen circumstances. A multisensor core logger (MSCL, Geotek Ltd.) was deployed to the Tugen Hills/Baringo and West Turkana sites to collect MS data on unsplit cores during drilling, but the MSCL was not available for the remaining sites.

After drilling each site, cores were shipped via airfreight to LacCore, the National Lacustrine Core Facility (University of Minnesota) for full scanning, processing, description, and subsampling. Physical properties for cores from all sites were analyzed in detail via MSCL-S (whole core, for p wave velocity, gamma density, loop MS, non-contact electrical resistivity, natural gamma radiation) and MSCL-XYZ (split core, for high-resolution MS and color reflectance spectrophotometry) at increments ranging from 0.5 to 4 cm, depending on the parameter. Cores were split in half lengthwise, cleaned, and scanned with a Geotek© MSCL-CIS digital linescan core imager. Visual core description, smear slide analysis, and (as needed) SEM-EDS and XRD analyses were performed, and subsamples were extracted according to coordinated plans for stratigraphically equivalent samples for all analytical parameters.

5 Initial coring and core description results

In total, 18 boreholes were drilled in the HSPDP (Table 1), although several of these were "deadman" anchoring holes to secure the drill rig and not intended for core recovery. Approximately 2 km of core was recovered from about 2200 m of cored intervals, for an average recovery of ~ 90.5 %. The only area where recovery was significantly below this average was at the Lake Magadi site, where interbedded hard and soft lithologies (cherts and unconsolidated muds) made for extremely challenging coring conditions.

Six boreholes were drilled at the Northern Awash area from two sites (NAO/Osi Isi and NAW/Woranso, Fig. 2a), which yielded approximately 650 m of core. The longest single borehole was ~ 244 m (NAW-1A), but, because of the offset between the stratigraphically higher top of NAO (about 25 m above the top of NAW) we estimate the total strati-

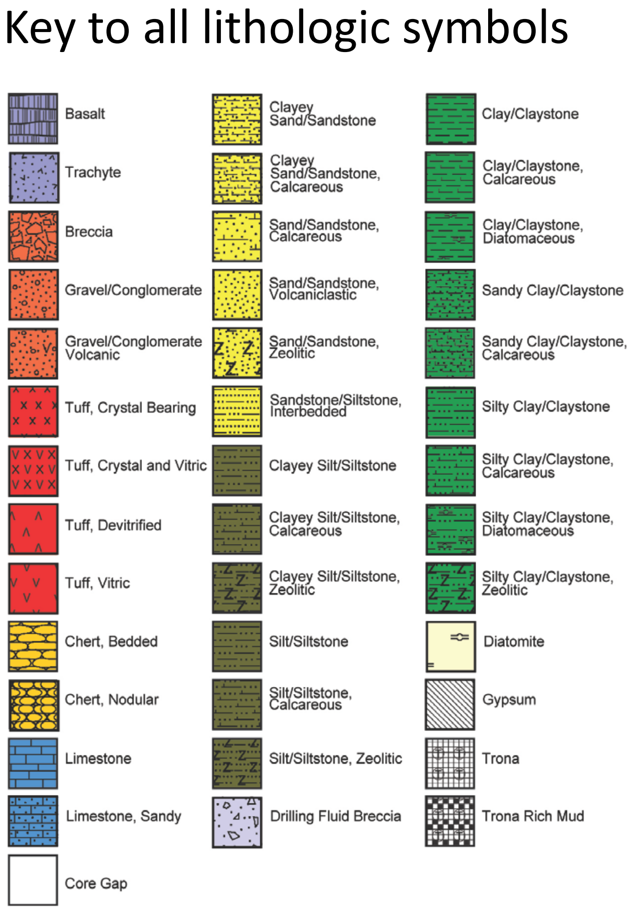

Figure 4. Key to all lithologic symbols. Note that blank (white) areas in lithologic columns indicate zones of missing core, i.e., no core recovery.

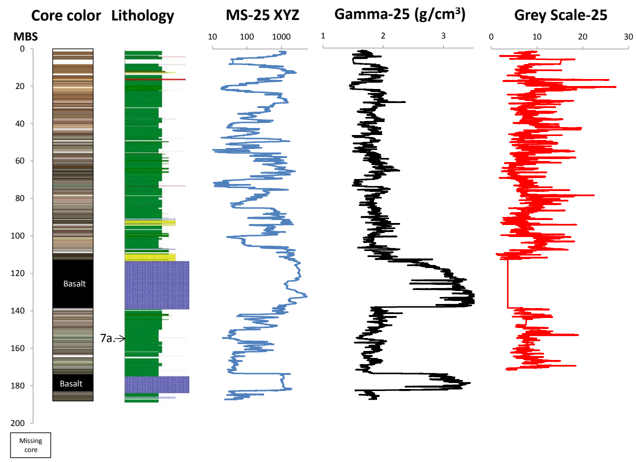

Figure 5. Summary stratigraphy of core HSPDP-NAO14-1B, from the Oso Isi locality, Northern Awash drilling area, northern Ethiopia, based on initial core description results. Columns from left to right: core color stratigraphy (from XYZ spectrophotometric imaging data, adjusted in Photoshop© to using Image Adjustment Levels to maximize color range). Basalt intervals were not imaged and are shown as solid black and missing core intervals are shown in white; lithologic log, rendered in PSICAT©. See Fig. 5 for the key to lithologies used in all cores illustrated. Zones with missing cores are indicated by blank intervals. Letter/number markers and arrows to the left of the lithologic log indicate the position of corresponding core photos in Fig. 7 for this and other summary stratigraphy figures; composite of magnetic susceptibility (MS) log data from the LacCore Geotek© XYZ point sensor data on split core segments, measured at 0.5 cm increments. Data have been smoothed (25-point running mean smooth, hence MS-25, Gamma-25, and Grey Scale-25); composite of induced gamma density log data at 0.5 cm increments from the LacCore Geotek© Multisensor Core Logger (MSCL). Spurious values ($< 1.4\,\mathrm{gm\,cm^{-3}}$) caused by coring gaps have been removed prior to analysis and plotting. Data have been smoothed (25-point running mean); composite of spectrophotometric grey-scale log data at 0.5 cm increments from the LacCore Geotek© XYZ spectrophotometric sensor. Data have been smoothed (25-point running mean).

graphic interval covered by the two sites to be approximately 270 m. Boreholes consisted of three primary science boreholes inclined 13–15°, plus two cored anchoring holes and one uncored hole, all of which were drilled in February–March 2014. Thick basalt sections were encountered at both sites (some of which appear to be compound flows), which are separated by about 3 km. Sediments at both drill sites are gently dipping (∼ 2° NE). The two longest cores (NAO-1B, Fig. 5 and NAW-1A, Fig. 6) consist of primarily massive or laminated, brown or greenish brown silty clays, with occasional sandy units scattered through the core, particularly associated with the upper basalt (Fig. 7a, b). Diatomites occur sporadically, mostly in the upper portions of both cores, with diatomaceous units more abundant below the second basalt. Thin (mm–cm) unaltered airfall volcanic ashes occur throughout the core. Most of the pronounced low-MS and low gamma density zones consist of either diatomites or fine, greenish clays. The brown clays contain abundant paleosol nodules and occasional beds of gastropods. Drilling at both the NAO and NAW localities was terminated when advancing the holes became impractical as rods became stuck because of very tight hole conditions, very high torque, and water pressure.

A single, vertical ∼ 228 m borehole was drilled at the Tugen Hills site in May–June 2013 (Fig. 8). The borehole was situated in very close proximity to exposures of variably dipping (20–42° in the borehole) cyclic diatomites and mudstones of the upper Chemeron Formation, which had previously been shown by Deino et al. (2006) and Kingston et al. (2007) to reflect extreme precessional climate variability in the central Kenyan Rift during the Plio-Pleistocene transition. The lower ∼ 100 m of the core is coarser on average than the upper part of the core. From the base to ∼ 130 m b.s. the core contains frequent channelized granular sands and conglomerate beds (often reddish in color), alternating with carbonate nodular paleosol siltstones (Fig. 7c), with sparse

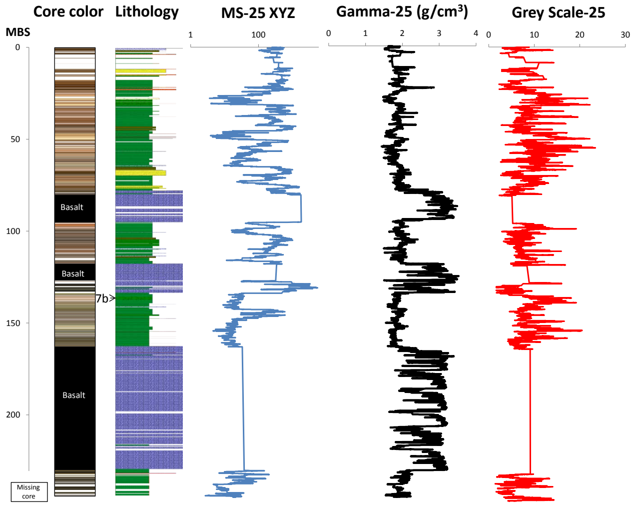

Figure 6. Summary stratigraphy of core HSPDP-NAW14-1A, from the Woranso locality, Northern Awash drilling area, northern Ethiopia, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values < 1.4 gm cm^{-3} removed); composite of spectrophotometric grey-scale log data (25-point running mean smooth). All data collection, instrumentation, and parameters as in Fig. 5.

lacustrine muds and diatomites. Above this, diatomite lacustrine/terrestrial cycles similar to those seen in outcrop begin to appear (evident in both the lithologies and physical properties of the upper portion of the drill core, Fig. 7d). Low-density, low-magnetic-susceptibility sediments (light colored lacustrine diatomites and clays) alternate with more strongly magnetically susceptible and denser siliciclastic muds (paleosols, often with abundant carbonate nodules) and fluvial sands (and occasional gravels) in the upper 130 m of the core. Sediments above ∼ 50 m b.s. are generally lighter in color (note grey-scale data, Fig. 8), which may reflect near-surface weathering/alteration above the local water table. Numerous primary and reworked tephras occur throughout the core, which will be critical for dating the core. Drilling was terminated at this site close to the original planned target depth (250 m) for budgetary reasons.

A single, oriented (10° from vertical) ∼ 216 m borehole was drilled at the West Turkana (WTK) site in June–July 2013 (Figs. 2c, d and 9). The drill site was chosen to be in close proximity to outcrop exposures of the correlative Nachukui Formation, which is locally dipping at ∼ 5° W. The lower ∼ 155 m (61–216 m b.s.) of the core consists of laminated to massive green and brown clays, which are often fossiliferous (fish, ostracodes and molluscs, the latter often organized as discrete shell lags) (Fig. 7e). Many of these lacustrine clays contain paleosol structure and carbonate nodules indicative of episodic exposure and pedogenesis. Above 61 m b.s., a pronounced lithologic transition occurs towards coarser sediments (more frequent sandy intervals), which is also reflected in changes in the color and magnetic susceptibility of the core. Soil structure and nodular carbonates occur in these sediments as well. Tuffs occur as discrete horizons at several depths within the core, which at this locality will be critical for tephrostratigraphic correlation with nearby outcrops. Drilling was terminated at this site when borehole instability, high torque, and high-pressure groundwater caused an inability for the drilling to advance. Bottom hole temperatures also began to rise abruptly near the base of the hole, indicating a potential hydrothermal hazard.

Three vertical boreholes were drilled (and two cored) at the northern end of the Koora Plain, in the southern Kenya Rift Valley, ∼ 22 km SSW of the Olorgesailie archaeological site in September–October 2012 (Figs. 2d, 10, and 11). Because the DOSECC soft sediment tools were not available at this time, the upper, unconsolidated sediments of both boreholes were auger drilled and cuttings were bagged at Site 1. Excellent core recovery was achieved at both sites below the augered intervals (Table 1 and Figs. 10 and 11). Both cores consist of flat-lying, interbedded muds (laminated in part), diatomites, and fine to coarse sands, with some pumice-rich gravel and conglomerate intervals and infrequent carbonate marls as well. Numerous tuffs are also present. Both cores bottomed in the trachyte basement that underlies the basin at depths of ∼ 166 and 116 m for Sites 1 and 3, respectively.

Four vertical boreholes at two sites were drilled into flat-lying sediments at Lake Magadi in June 2014, and downhole logs were made in the single borehole at Site 2 (Figs. 3a, 12, 13). Unlike other sites, it was necessary to drill from a raised pad at Lake Magadi, because the surface trona crust was inundated and soft from recent rains. A custom-built pad was constructed by the project for Site 1 adjacent to the main causeway crossing the lake, whereas Site 2 took advantage of a wide area along another existing elevated roadbed on the playa. Also in contrast to the other drilling targets, the Lake Magadi sediments consist of large proportions of trona (Fig. 7f) and other Na carbonates and chert (Fig. 7g, as well as both laminated (Fig. 7h) and massive lacustrine muds. Muds, mudstones, and cherts in varying proportions dominate the lower stratigraphic intervals at both sites, whereas the upper portion at both sites is a 30–40 m thick sequence of trona and trona-bearing muds, the production target for Tata Chemicals, our local industry partner for this drill site. The upper trona was drilled using freshwater as the drilling fluid in the initial holes because bentonite drilling mud would not mix with the high-pH brines readily available near the site. However, this strategy proved problematic because dissolution cavities formed around the borehole, undermining site stability. For boreholes 1C and 2A drilling used only the high-pH lake brine without bentonite, which ultimately proved satisfactory because the high density of the brine was sufficient to raise the cuttings. The alternation of soft and

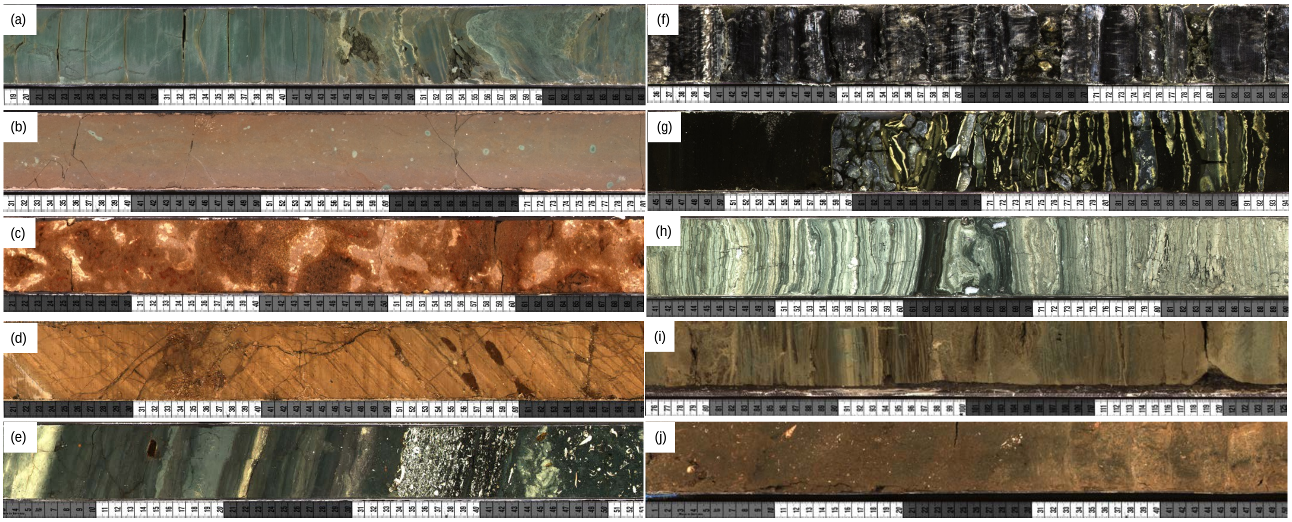

Figure 7. Representative lithologies found in HSPDP drill cores. Positions of each photo within the cores are indicated on the respective summary stratigraphy diagrams. NAO14-1B-66Q-1 (154.66–155.07 m below surface – m b.s.) from the Northern Awash Oso Isi site, northern Ethiopia. Note: many coring gaps in NAO14-1B are infilled by matching to the twinned borehole NAO14-1D (not illustrated), collected immediately adjacent to this core. Laminated green lake clays with soft sediment deformation. NAW14-1A-71Q-2 (138.60–139.06 m b.s.) from the Northern Awash Woranso site. Massive brown, silty, diatomaceous clay. BTB13-1A-52Q-2 (150.21–150.71 m b.s.) from the Baringo-Tugen Hills site, central Kenya. Well-developed paleosol with carbonate nodules. BTB13-1A-3Q-1 (9.85–10.35 m b.s.) from the Baringo-Tugen Hills site. Laminated diatomite with carbonate interbeds. WTK13-1A-63Q-1 (150.16–150.66 m b.s.) from the West Turkana drill site, northern Kenya. Green silty clays with mollusc coquinas. MAG14-2A-9Y-1 (19.58–20.08 m b.s.) from Lake Magadi, southern Kenya. Interbedded trona and thin muds. MAG14-1A-49Y-1 (75.02–75.52 m b.s.) Interbedded black silty clay and yellow/black chert. MAG14-2A-67Y-1 (147.10–147.60 m b.s.) from Lake Magadi. Laminated muds. CHB14-2A-35A-2A (73.22–73.72 m b.s.) partly laminated green and brown muds from the Chew Bahir Basin. CHB14-2A-70Q-1A (146.58–147.05 m b.s.) brown, mollusk-bearing massive mudstones from the Chew Bahir Basin.

lithified muds and cherts (often on a sub-meter depth scale) proved a challenging coring environment. Percent core recovery at this site (in the 45–65 % range) was consequently below the levels achieved at other sites. Drilling at both locations was terminated when the boreholes reached the trachytic basement rocks (at depths of ∼ 136 and 197 m for Sites 1 and 2, respectively).

An exploratory shallow coring campaign was conducted at the Chew Bahir area in 2009 and 2010 along a NW–SE transect from the basin margin to the center, which recovered six short sediment cores of 9–18.8 m length (Foerster et al., 2012, 2015; Trauth et al., 2015). Subsequently, a pilot drilling operation was conducted in the center of the Chew Bahir basin in March 2014 (∼ 41 m vertical borehole). Drilling at this site was terminated when flooding made the drilling site inaccessible. This was followed by the drilling of two considerably deeper, twinned vertical boreholes (∼ 279 and 266 m in flat-lying sediments for boreholes 2A and 2B, respectively, Figs. 14, 3b) in a slightly more proximal and elevated position relative to the basin margin in November–December 2014. The CHB14-2A and 2B cores consist predominantly of reddish, brown or green silty and sandy clays, with occasional silt and calcareous sand beds. Discrete shell-rich and plant debris-rich horizons occur throughout the cores. Carbonate nodule-rich muds are more common in the lower part of the core (below ∼ 90 m b.s.). Drilling was terminated when advancing became impractical and funds were depleted.

6 HSPDP outreach and education activities

The HSPDP has made a priority of developing an effective outreach and educational program that makes the project's goals and findings accessible to the broader public. Prior to and during drilling activities at each study area, an intensive effort was made to engage with the local public about our activities. This often involved having Kenyan and Ethiopian research and museum outreach specialists make presentations using visual aids such as segments of sediment cores or casts of hominin skulls to explain the science objectives and (importantly) to dispel misunderstandings concerning the nature of our drilling activities (which were commonly assumed to be for resource exploration prior to these presentations) (Fig. 3c). The HSPDP has also worked closely with the National Museums of Kenya and Ethiopia, as well as several museum institutional partners in the US, in the development of post-drilling educational resources that these museums can use in the future to explain the intersection between human evolutionary history and climate history. The most

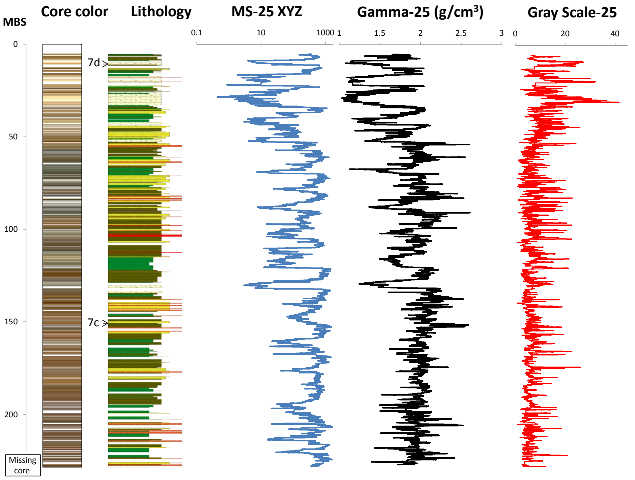

Figure 8. Summary stratigraphy of core HSPDP-BTB13-1A, from the Tugen Hills drilling area, central Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values $< 1.0\,\mathrm{gm\,cm^{-3}}$ removed; n.b.: lower threshold used than for NA cores because of abundant dry and porous diatomites); composite of spectrophotometric grey-scale log data (25-point running mean smooth). All other data collection, instrumentation, and parameters as in Fig. 5.

visible of these efforts has the been the development of a short (14 min) 3-D film, produced by the nonprofit Earth Images Foundation (www.earthimage.org), and funded jointly by the US National Science Foundation and ICDP, which documents both the important science questions underpinning the HSPDP as well as the excitement associated with the drilling and core analysis activities (Fig. 3d). This film will be on long-term display in the human origins halls at the partner museums, and is also available in 2-D format via the project website (http://hspdp.asu.edu) and Facebook page (www.facebook.com/HSPDP). The HSPDP has a strong social media presence through its Facebook site and project website, where educational resources, such as numerous photographs of drilling and initial core description activities are made available to the general public. Another exciting and innovative HSPDP outreach activity has been the involvement of an "artist in residence", funded through our UK NERC grant. The artist, Julian Ruddock, will be using high-resolution photographs and video footage including interviews he has conducted during drilling activities at the Chew Bahir site, as well as core images to create an art/science collaboration for gallery display in the UK starting in 2016 http://cargocollective.com/artscienceclimatechange/Earth-Core-The-Hominin-Project. HSPDP members, led by co-PI Martin Trauth, are currently teaching a series of sum-

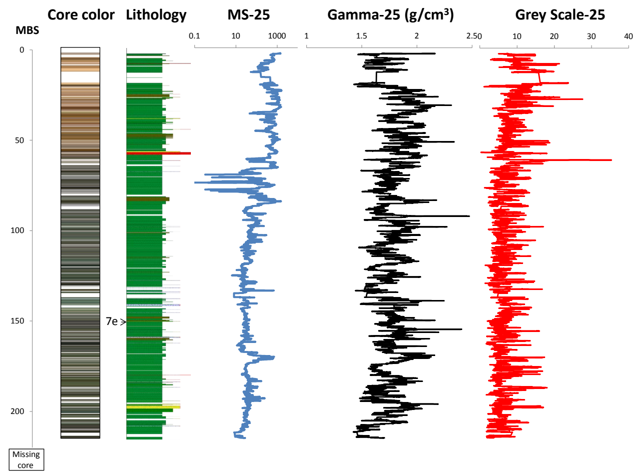

Figure 9. Summary stratigraphy of core HSPDP-WTK13-1A, from the West Turkana drilling area, northern Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values $< 1.4\,\mathrm{gm\,cm^{-3}}$ removed); and composite of spectrophotometric grey-scale log data (25-point running mean smooth). All data collection, instrumentation and parameters as in Fig. 5.

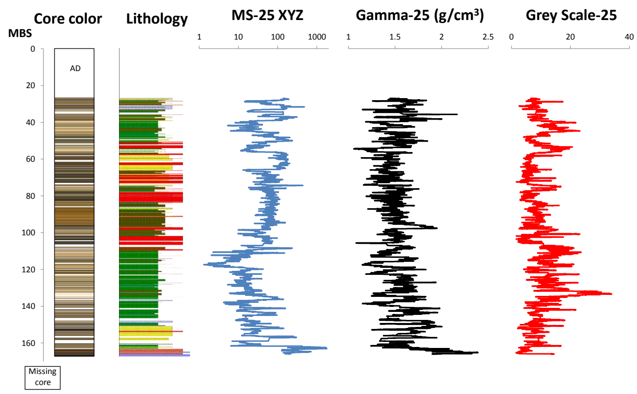

Figure 10. Summary stratigraphy of core ODP-OLO12-1A, from the Koora Plain/Olorgesailie drilling area, southern Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values $< 1.0\,\mathrm{gm\,cm^{-3}}$ removed); and composite of spectrophotometric grey-scale log data (25-point running mean smooth). AD: auger drilled sediment samples were bagged and collected in 1 m intervals. All other data collection, instrumentation, and parameters as in Fig. 5.

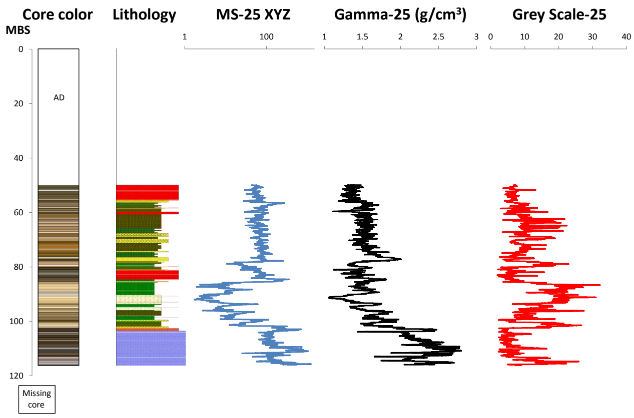

Figure 11. Summary stratigraphy of core ODP-OLO12-3A, from the Koora Plain/Olorgesailie drilling area, southern Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values < 1.0 gm cm^{-3} removed); composite of spectrophotometric grey-scale log data (25-point running mean smooth). AD: augered drilled interval: sediment bagged and collected at Site 1, and not collected at Site 3. All other data collection, instrumentation, and parameters as in Fig. 5.

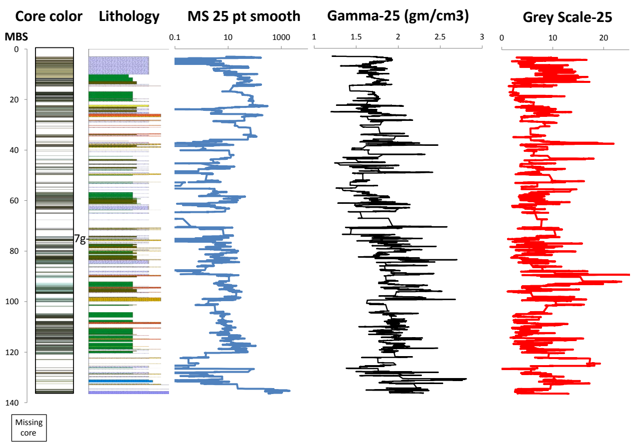

Figure 12. Summary stratigraphy of composite core HSPDP-MAG14-1A + 1C (basal portion of 1C core below 125 m only), from the Lake Magadi drilling area, southern Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values < 1.2 gm cm^{-3} removed); composite of spectrophotometric grey-scale log data (25-point running mean smooth). All data collection, instrumentation, and parameters as in Fig. 5.

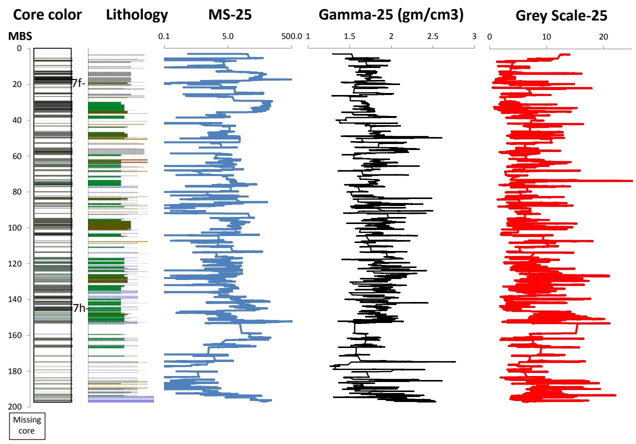

Figure 13. Summary stratigraphy of core HSPDP-MAG14-2A, from the Lake Magadi drilling area, southern Kenyan Rift Valley, based on initial core description results. Columns from left to right: core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values < 1.2 gm cm^{-3} removed); composite of spectrophotometric grey-scale log data (25-point running mean smooth). All data collection, instrumentation, and parameters as in Fig. 5.

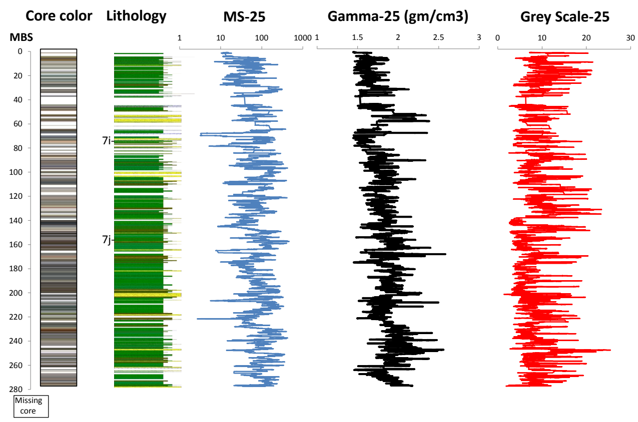

Figure 14. Summary stratigraphy of core HSPDP-CHB14-2A, from the Chew Bahir drilling area, southern Ethiopian Rift Valley, based on Initial Core Description results. Note: coring gaps in CHB14-2A are almost entirely infilled by matching to the twinned borehole CHB14-2B (not illustrated), collected immediately adjacent to this core. Columns from left to right: Core color stratigraphy; lithologic log; see Fig. 5 for the key to lithologies used in all cores illustrated; composite of magnetic susceptibility (MS) log data (25-point running mean smooth) from LacCore Geotek© XYZ point sensor data; composite of induced gamma density log data (25-point running mean smooth, spurious values < 1.4 gm cm^{-3} removed); composite of spectrophotometric grey-scale log data (25-point running mean smooth). All data collection, instrumentation, and parameters as in Fig. 5.

mer schools in the bio-geosciences that help twenty young scientists from African and European universities to design new research projects on these topics, using the latest methods of data analysis, and to present the results from these projects in an attractive and professional manner. The overall topic of the summer school, held in Ethiopia (September–October 2015) and Kenya (February–March 2016), is tectonics, climate, and human evolution, using the latest results from the HSPDP as the basis of discussions during the event.

7 Future plans

Now that all HSPDP-related drilling is completed, all cores are being analyzed for a wide variety of geochronological, geochemical, sedimentological and paleoecological studies, to assemble a high-resolution record of environmental change at each of the study sites. The geochronology of the cores is being assembled through a combination of high-precision Ar/Ar, paleomagnetics, U-series, tephrostratigraphy, luminescence and (for the most recent parts of the cores) ^{14}C dating. State-of-the-art organic geochemical and clumped isotope proxies of paleotemperature and paleoprecipitation are being applied to the cores. The wide array of fossils (diatoms, ostracodes, molluscs, fish, pollen, phytoliths and charcoal) are also being exploited for the information they provide about both lake and watershed paleoecological conditions. Scanning XRF, XRD, and MSCL log records are also providing extremely high-resolution records of paleoenvironmental and provenance history at each site. Another important component of this analysis is the integration of core data with nearby outcrop information about paleoenvironments of *hominins* and other fossils and stone tools. Extensive interaction between the data collection and modeling teams of the HSPDP is also underway, to ensure that plausible explanations of climate and landscape dynamics are developed and tested against the core and outcrop data. Ultimately, through interaction between the core analysts and paleoanthropologists involved in the HSPDP, we hope to use our new high-resolution core data and climate/landscape models to both re-evaluate existing models linking hominin evolution with climate and propose new ones consistent with the vast new data set assembled by the HSPDP.

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Scientific Drilling
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IODP Expedition 337: Deep Coalbed Biosphere off Shimokita – Microbial processes and hydrocarbon system associated with deeply buried coalbed in the ocean

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Abstract. The Integrated Ocean Drilling Program (IODP) Expedition 337 was the first expedition dedicated to subseafloor microbiology that used riser-drilling technology with the drilling vessel *Chikyu*. The drilling Site C0020 is located in a forearc basin formed by the subduction of the Pacific Plate off the Shimokita Peninsula, Japan, at a water depth of 1180 m. Primary scientific objectives during Expedition 337 were to study the relationship between the deep microbial biosphere and a series of ∼2 km deep subseafloor coalbeds and to explore the limits of life in the deepest horizons ever probed by scientific ocean drilling. To address these scientific objectives, we penetrated a 2.466 km deep sedimentary sequence with a series of lignite layers buried around 2 km below the seafloor. The cored sediments, as well as cuttings and logging data, showed a record of dynamically changing depositional environments in the former forearc basin off the Shimokita Peninsula during the late Oligocene and Miocene, ranging from warm-temperate coastal backswamps to a cool water continental shelf. The occurrence of small microbial populations and their methanogenic activity were confirmed down to the bottom of the hole by microbiological and biogeochemical analyses. The factors controlling the size and viability of ultra-deep microbial communities in those warm sedimentary habitats could be the increase in demand of energy and water expended on the enzymatic repair of biomolecules as a function of the burial depth. Expedition 337 provided a test ground for the use of riser-drilling technology to address geobiological and biogeochemical objectives and was therefore a crucial step toward the next phase of deep scientific ocean drilling.

1 Introduction

Subseafloor sediments harbor a remarkable number of microbial cells, with its concentrations decreasing logarithmically with increasing burial depth (Parkes et al., 1994; D'Hondt et al., 2004; Lipp et al., 2008; Kallmeyer et al., 2012). Active microbial populations exist at great depths below the ocean floor, which can only be explored by scientific ocean drilling. For example, the Integrated Ocean Drilling Program (IODP) Expedition 317 found microbial cells in sediments of the Canterbury Basin, off the coast of New Zealand, down to 1922 meters below the seafloor (m b.s.f.) (Site U1352, 344 m water depth; Ciobanu et al., 2014). However, the extent of the deep biosphere and factors limiting life at its lower boundaries remain largely unknown. For similar reasons, microbial ecosystems in marine subsurface hydrocarbon reservoirs on the continental margin are among the least characterized systems on Earth. In fact, our knowledge base of the interactions of the deep biosphere with offshore hydrocarbon reservoirs has long suffered from the highly limited opportunities to target natural gas and oil fields with scientific ocean drilling initiatives. Despite the biogeochemical significance of hydrocarbon reservoirs for the global carbon cycle (Head et al., 2003; Jones et al., 2008), there have been no studies of coal layers that are deeply buried in the subseafloor, mainly because of the safety regulations related to hydrocarbon gas-related hazards during non-riser-type drilling. In continental sediments, large quantities of gaseous hydrocarbons and their derivatives (e.g., H_2, organic acids) are potentially generated via thermogenic and/or biogenic degradation processes of deeply buried organic matter such as lignite coals (e.g., Jones et al., 2008; Glombitza et al., 2009; Strąpoć et al., 2008, 2011). Such diagenetic products are potential nutrient and energy sources that support energy-yielding redox reactions mediated by deep subseafloor microbial communities. Hence, coalbeds and microbial life may influence characteristics of dissolved gases and organic matter in the subsurface and result in the accumulation of gas hydrates in shallow sedimentary strata. The metabolic characteristics of organic matter degradation and the fluxes of secondary metabolites, however, still remain largely unknown (Hinrichs et al., 2006; Hinrichs and Inagaki, 2012). To explore the limits of microbial life and the biosphere and understand microbial processes in the deeply buried coalbeds, Expedition 337 examined the hydrocarbon system associated with deeply buried coalbeds off the Shimokita Peninsula, Japan, in the northwestern Pacific using the riser-drilling system of *Chikyu* (Inagaki et al., 2012).

2 Geological background

The drilling Site C0020 is located in a forearc basin formed by the subduction of the Pacific Plate (~ 8 cm year^{-1}, west-northwest plate motion vector: Seno et al., 1996) beneath northeastern Honshu, Japan (Fig. 1). During the *Chikyu* shakedown cruise CK06-06 in 2006, 365 m of sediment core were recovered from the upper sedimentary section at Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Site C9001 (41°10.5983′ N, 142°12.0328′ E, 1180 m water depth, i.e., the same location as IODP Site C0020), approximately 80 km off the coast of Shimokita Peninsula of Japan (Aoike, 2007). Preliminary biostratigraphic age models indicated very high sedimentation rates, ranging from 54 to 95 cm kyr^{-1}, and an approximate core-bottom age of 640 ka (Aoike, 2007; Aoike et al., 2010; Domitsu et al., 2010). During the same cruise, riser drilling was also tested down to 647 m b.s.f. without coring, and 20" casings were installed down to 511 m b.s.f., and then the riser hole was suspended for future operations including the IODP Expedition 337.

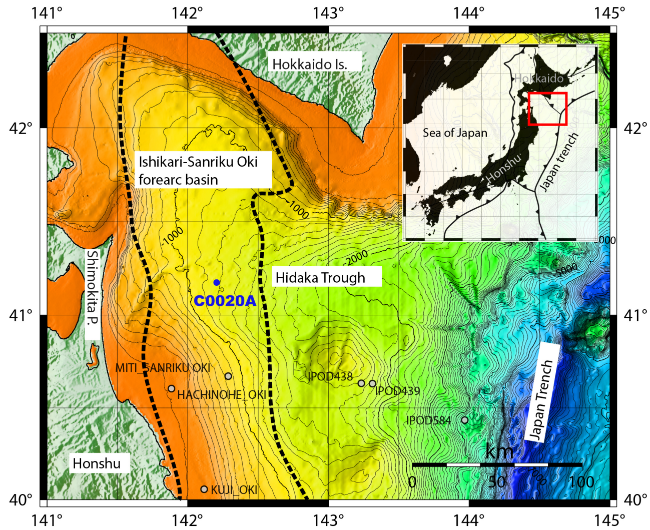

Figure 1. Bathymetric map of IODP Site C0020 (JAMSTEC Site C9001) and existing drill holes off the Shimokita Peninsula, Japan. Inset map shows plate configuration around Japanese islands and the location of the index map (gray square). This figure is slightly modified from Fig. S1 in Inagaki et al. (2015), and reprinted with permission from American Association for the Advancement of Science (AAAS).

The Hidaka Trough, a sedimentary basin formed by subsidence in the drilling area, originates just offshore southwest of Hokkaido and extends to the Japan Trench. Along the coastal area of the Shimokita Peninsula, both sedimentary and volcanic rocks younger than Late Cretaceous lie scattered on Triassic to Early Cretaceous sedimentary rocks or Cretaceous granites. Several scientific drilling expeditions have been carried out off the Shimokita Peninsula: Deep Sea Drilling Program (DSDP) Legs 56 and 57 in 1977, Leg 87 in 1982, and Ocean Drilling Program (ODP) Leg 186 in 1999. In addition, well data are available from hydrocarbon drilling exploration carried out between 1977 and 1999 (Japan Natural Gas Association and Japan Offshore Petroleum Development Association, 1992; Osawa et al., 2002). Seismic profiles around Site C0020 show pull-up blanking reflections below bottom-simulating reflectors at around 360 m b.s.f., suggesting the occurrence of methane hydrates in shallow sedimentary realms and a strong upward flux of free hydrocarbon gases from deep reservoirs. A thick and prominent Quaternary sedimentary unit onlaps to a Pliocene unit and is thought to be composed mainly of alternating beds of mud and sand with intercalations of thin volcanic tephras and locally developed gravel/sand layers. The Pliocene unit consists primarily of alternating beds of mudstone and sandstone. Below these relatively recent formations, there are sedimentary deposits ranging from Cretaceous to Miocene in age that are cut by many landward-dipping normal faults. The presence of coal formations underneath the seafloor has been confirmed by the natural gas drilling exploration at nearby site MITI Sanriku-Oki, approximately 50 km southward from Site C0020 (Fig. 1; see Osawa et al., 2002). Sonic logging data in the MITI Sanriku-Oki well showed that three major tuff layers involving coal layers with 30, 45, and 80 m thickness (40–60 % total organic carbon (TOC) in lignite coal layer and 0.5–2 % TOC in tuffs) are present in Eocene and Pliocene–Upper Cretaceous horizons, in which vitrinite reflection values (Ro) were in the range between 0.5 and 0.7 %, indicating relatively immature coals. The in situ temperatures are well within the range of the habitable zone of microbes, based on the reported thermal gradient of 22.5 °C km^{-1} (Osawa et al., 2002).

3 Microbiological background

During the *Chikyu* shakedown expedition CK06-06 at the drilling site later occupied during Expedition 337, the shift of microbial communities in the first use of riser-drilling mud tanks and circulated drilling fluids was examined through cultivation and cultivation-independent microbiological studies (Masui et al., 2008). Despite the high alkalinity of the riser-drilling mud ($\sim$ pH 10), the predominance of *Xanthomonas* DNA as well as the potential growth of facultatively anaerobic and halophilic bacteria *Halomonas* were observed in the mud tank sample.

Microbial cell numbers in 365 m sediment from Site C9001 were evaluated by the fluorescent image-based automated cell count system, showing that the sediment contained abundant microbial cells with counts over 10^7 mL^{-1} down to 365 m b.s.f. (Morono et al., 2009; Morono and Inagaki, 2010). The relative abundance of Bacteria and Archaea was studied by quantitative polymerase chain reaction (PCR) and slot-blot hybridization techniques, suggesting a significant contribution of Archaea to the subseafloor microbial biomass (average 30–40 % at DNA level) (Lipp et al., 2008). Using a deep sediment sample from Site C9001, carbon and nitrogen incorporation rates of sedimentary microbes were studied using nano-scale secondary-ion mass spectrometry (NanoSIMS), indicating that the deeply buried microbial cells are indeed alive and capable of carbon and nitrogen uptake into their cellular biomass (Morono et al., 2011). Taxonomic compositions of microbial communities in 365 m of sediment cores were investigated by analyzing PCR-amplified 16S rRNA and some key functional genes (Futagami et al., 2009; Morono et al., 2014; Aoki et al., 2015; Nunoura et al., 2016) as well as the metagenomic sequences (Kawai et al., 2014, 2015), indicating the occurrence of microbial communities that have been often detected in organic-rich sediments on the Pacific margins (e.g., Inagaki et al., 2003, 2006), such as bacterial members of the phyla "Atribacteria", Chloroflexi, Planktomycetes, and Firmicutes, and archaeal members of the "Bathyarchaeota" (previously classified as the Miscellaneous Crenarchaeota Group, MCG), Marine Benthic Group-B (alternatively, Deep-Sea Archaeal Group (DSAG) or "Lokiarchaeota"), and South African Gold Mine Euryarchaeota Group (SAGMEG).

Cultivation of aerobic and anaerobic microorganisms has been conducted at Site C9001 and a variety of microbes and their enzymatic activities were observed (Kobayashi et al., 2008). Using a continuous-flow bioreactor system called down-flow hanging sponge reactor, phylogenetically diverse, strictly anaerobic microbes were also successfully cultivated, including methanogens such as the genera *Methanobacterium*, *Methanoccoides*, and *Methanosarcina* (Imachi et al., 2011). Several attempts of traditional batch-type cultivations also successfully led to the pure culture isolation of several subseafloor anaerobic microbes, including new Bacterioidetes species of *Geofilum rubicundum* (Miyazaki et al., 2012) and *Sunxiuqinia faeciviva* (Takai et al., 2012), new *Spirochaetes* species of *Spirochaeta psychrophila* and *Sphaerochaeta multiformis* (Miyazaki et al., 2014a, b), and a new species of a new genus of *Pelolinea submarina* within the phylum *Chloroflexi* (Imachi et al., 2014).

4 Scientific objectives

During Expedition 337, we tackled a number of fundamental questions regarding deep subseafloor hydrocarbon systems. For example:

– What role does subsurface microbial activity play in the formation of hydrocarbon reservoirs?

– Do deeply buried hydrocarbon reservoirs, such as natural gas formations and coalbeds, act as geobiological reactors that sustain subsurface life by releasing nutrients and carbon substrates?

– Do the conversion and transport of hydrocarbons and other reduced compounds influence biomass, diversity, activity, and functionality of deep subseafloor microbial populations?

– What are the fluxes of both thermogenically and biologically produced organic compounds and how important are these for the carbon budgets in the shallower subsurface and the ocean?

– What paleoenvironmental information and sedimentary regimes are recorded at Site C0020?

– What is the extent of the subseafloor biosphere? What environmental factors define the lower boundaries of the biosphere?

5 Expedition summaries

5.1 Coring, drilling, and logging operations

The *Chikyu* left Hachinohe Port to Site C0020 on 26 July 2012. The corrosion cap of Hole C9001D, which was drilled to 647 m b.s.f. and cased to 511 m b.s.f. during the *Chikyu* shakedown cruise in 2006, was retrieved at the surface on 27 July. Ten transponders were installed on the seafloor by a remotely operated vehicle on 28 July, and failure mode effect analysis for acoustic position reference system was completed on 29 July.

While the surface pressure test of the blow out preventer (BOP) was being carried out, the science party was shuttled on board by helicopter flights on 31 July. Technical problems were found during the function test of the BOP and troubleshooting continued until 8 August. A successful BOP landing was confirmed on 11 August. Extensive BOP tests were carried out until completion of the pressure test on 14 August. Subsequently, riser drilling started. Due to the delay in operations, planned spot-coring in the interval 647–1220 m b.s.f. was canceled and instead a 17-1/2″ hole was established and cemented to a depth of 1220 m b.s.f. On 16 August, we encountered total mud loss at 2375 m drilling depth below rig floor (DRF). After spotting lost circulation mud twice, mud loss rate decreased to 0.8 $m^3 h^{-1}$. A decision to continue drilling with seawater gel mud was made. Drilling resumed on 18 August and reached at 2471.5 m DRF (i.e., 1263 m b.s.f.); to this depth 13-3/8″ casing was installed.

Coring operation started on 25 August. While riser drilling continued, spot cores were taken by rotary core barrel (RCB) until core 7R hit a low rate of penetration interval at 1604.0 m b.s.f. The core included gravels of volcanic origin and showed different lithology from previous cores. To retrieve core samples at this depth, an industry-type large diameter core (LDC) was tested. The LDC operation was, however, stopped before reaching the targeted 27 m of drilling advance, because an increase in pump pressure and no further penetration indicated core jamming. The LDC was recovered on deck on 30 August and the recovered core was 10.0 m from 21.5 m of advance. The core was cut into 1.0 m long sections at the middle pipe rack and transferred to the laboratory. Spot coring resumed with RCB and cores 9R to 14R were taken before continuous coring through the coal-bearing horizons started at 1919 m b.s.f. After four consecutive RCB cores were recovered, the drill bit appeared to be worn out. Consequently, it was decided to change the drill bit.

After coring of core 18R, it was also decided that we continue RCB coring and cancel a planned operation of the LDC. The new drill bit was installed and coring operations resumed on 4 September. Another seven consecutive RCB cores were taken from 1950 to 2003.5 m b.s.f. Core recovery was high, and coal-bearing sequences were obtained. With the successful sampling of various lithologies within and around the coal-bearing formation, our operational mission in this interval was fulfilled, and we then advanced the borehole by drilling and spot coring in 100 m intervals to more completely examine the hydrocarbon system and explore the limits of life at greater depths. We reached the terminal depth of Hole C0020A at 2466 m b.s.f. on 9 September, exceeding the previous deepest hole of scientific ocean drilling (i.e., 2111 m b.s.f., Hole 504B off Costa Rica, ODP Leg 148). The core recovery through riser drilling was remarkably high, often close to 100 %, even at great burial depths of 2000 m b.s.f. and deeper.

The condition of the riser borehole was excellent, allowing for close-to-perfect acquisition of downhole wireline logging data. After pulling out of the hole, wireline-logging operation started. Logging run 1 (PEX: platform express) started on 10 September, followed by runs 2 (FMI: formation microimager) and 3 (CMR: combinable magnetic resonance). High-permeability layers were selected for the Modular Formation Dynamics Tester (MDT) based on the results from the first three runs. After a wiper trip, run 4 (MDT-GR: MDT-gamma ray) started on 12 September. Pretests for fluid mobility and formation pressure measurements were carried out at 31 horizons. Formation fluid samples were taken by the Schlumberger's QuickSilver MDT-Probe at six horizons of high mobility, and the six bottles were recovered on deck on 14 September. The sample bottles were delivered to the laboratory during the following run 5 (VSP: vertical seismic profile). The last run was completed on 15 September, ending scientific operation on the rig floor.

5.2 Lithostratigraphy and biostratigraphic age

Four distinct lithologic units were identified at Site C0020 on the basis of combined analysis of cuttings and cores, and assisted by inspection of X-ray computed tomography (CT) scan images and wireline-logging data; 14 coal layers were confirmed between 1825 and 2466 m b.s.f. On-board micropaleontology included diatoms, calcareous nannofossils, organic-walled dinoflagellate cysts (dinocysts), pollen, and spores, indicating a probable age of late Oligocene to early Miocene at the base at 2466 m b.s.f. A stratigraphic column of the borehole is provided in Fig. 2. From top to base, the following units were described (Inagaki et al., 2012; Gross et al., 2015).

- Unit I (647–1256.5 m b.s.f.) consists primarily of diatom-bearing silty clay. This unit resulted from sedimentation in an offshore marine environment. Diatoms were best and most abundantly preserved in Unit I among monitored microfossils together with predominantly heterotrophic dinocysts. Diatom floras in Unit I are consistent with a Pliocene cool-water continental shelf succession. Heterotrophic dinocyst communities feeding off diatom blooms are suggestive of elevated marine productivity.

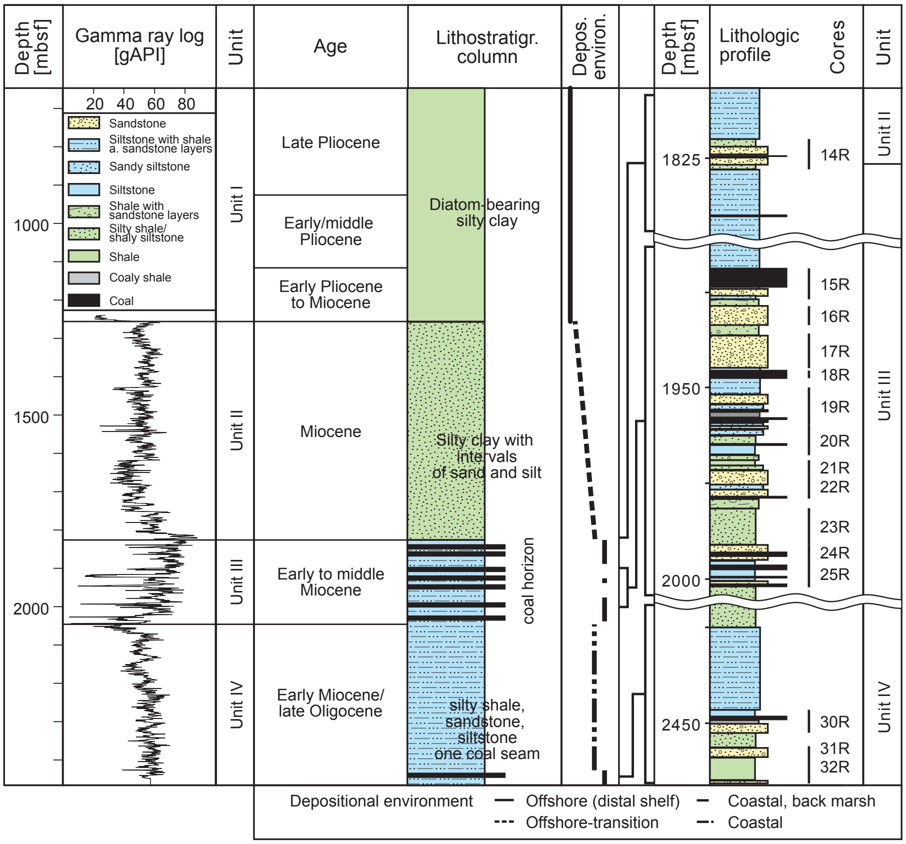

Figure 2. Lithologic profile of Hole C0020A based on macroscopic observation of cuttings (middle and right column) and cores (right column) recovered during Expedition 337. Gamma-ray log and positions of spot-cores are also plotted. This figure is slightly modified from Fig. 2 in Gross et al. (2015), and reprinted with permission from Elsevier.

- Unit II (1256.5–826.5 m b.s.f.) consists mostly of silty shale with some interspersed intervals of sandstone and siltstone. Cuttings samples show a lower amount of sand and an increase of silt at the Unit I/II boundary. The abundance of biogenic siliceous material, glauconite, and plant remains additionally differentiate Unit II from the overlying unit. Unit II was subdivided into two different subunits, sandstone and siltstone associated with marine fossiliferous material (Subunit IIa; 1256.5–1500 m b.s.f.) and organic-rich shale and sandstone associated with plant remains (Subunit IIb; 1500–1826.5 m b.s.f.). The upper part of Unit II represents an offshore paleoenvironment, possibly close to the shelf margin; with increasing depth the paleoenvironment gradually changes into a shallow marine setting. The bottom part of Unit II is situated in the intertidal zone. This shift is consistent with microfossil assemblages that exhibit few identifiable diatoms and poor dinocysts; reworked dinocyst in Unit II, as in deeper units, have Paleogene ages that broadly fall in the range of early–middle Eocene through to late Oligocene. Pollen and spores are moderately well represented but are abundant near the base of Unit II, consistent with an increasing terrestrial influence in shallow marine sediments.

- Unit III (1826.5–2046.5 m b.s.f.) is dominated by several coal horizons, which we subdivided into coaly shales, siltstones, and sandstones. Almost all coal horizons consist of fine-detritic to xylodetritic coal with some layers of xylitic coal. Water content, color, and vitrinite reflectance measurements of the coal suggest that the coal has low maturity. Bioturbation and sedimentary features like flaser bedding, lenticular bedding or cross-bedding suggest a near-shore depositional environment with tidal flats and tidal channels. The presence of siderite bands at the bottom of this unit suggests a back barrier marine environment in combination with wetlands (e.g., salt marsh or swamp). Small terrestrial influence (e.g., siderite grains) might occur within sand bodies that overlie coal horizons. This could be due to channels from deltaic environments. Unit III contains excellently preserved pollen and spore assemblages in the coals and associated terrestrial to coastal shallow marine sediments. However, dinocysts are scarce and contain few useful biostratigraphic markers. The pollen floras tentatively suggest a likely age of early–middle Miocene for Unit III.

- Unit IV (2046.5–2466 m b.s.f.) is dominated by silty shales in the upper part, sandstone, intercalated with siltstone, and shale associated with sand in the middle part and with silt and a thin coal layer in the lower part. Wireline logs and cuttings samples suggest a thick homogeneous shale layer between the Unit III boundary and core 27R at 2200 m b.s.f. The depositional environment of Unit IV resembles that of Unit III, except that the former contains only one thin coalbed layer. Like Unit III, Unit IV experienced high-frequency fluctuations of the depositional environment. Within a few meters, there are sediments related to tidal flats and tidal channels, which are overlain by organic-rich material of a marsh that resulted in formation of peat. The pollen floras place a maximum age of late Oligocene for the base of Unit IV.

5.3 Physical properties and downhole logging

A series of physical property measurements were performed on core and cuttings samples from Site C0020. Gamma-ray attenuation density, magnetic susceptibility, natural gamma radiation, *P* wave velocity, and noncontact electrical resistivity were measured with the multi-sensor core logger. Measurements of thermal conductivity were made mostly on working-half cores. Discrete samples taken from working-half and some whole-round core samples were applied to moisture and density (MAD) analyses to calculate the porosity, bulk density, grain density, and water content. *P* wave velocity analysis and electrical impedance analysis were made on cubic discrete samples. Cuttings samples were also applied to MAD analysis. Cuttings samples were separated into four categories: original bulk and sieved size categories of > 4.0, 1.0–4.0, and 0.25–1.0 mm. Large-size fraction of the cuttings samples were cut off cubic samples and applied to the *P* wave velocity analysis and the electrical impedance analysis. Anelastic strain recovery analysis was made on some whole-round cores. Vitrinite reflectance analysis was performed on some coaly samples, indicating generally low maturity of coal. Porosity of siltstone, sandstone, and shale gradually decreased with increasing depth (Fig. 3). Porosity corresponds to lithologic variation, with carbonate-cemented sandstone and siltstone having much lower values than non-cemented sandstone and siltstone. The porosity of coal does not deviate from the major trend of the other lithologies, although the coal may change the figures because of decompaction after the recovery. The cuttings also show a gradual decrease in porosity but have generally higher values than the core samples. Discrete core samples are likely more representative of in situ porosity than cuttings.

Due to the very good borehole condition, logging data were excellent quality, resulting in straightforward interpretation of these logging data with respect to lithology. The logging data generally compensated for the lack of cores, and ultimately led to the establishment of a database that fully reconstructs the sedimentation history at Site C0020 (Inagaki et al., 2012). Borehole temperature was measured with two types of logging tools. The maximum temperature at the bottom of Hole C0020A was estimated by examining the temperature build-up pattern during the logging operation. The estimated temperature gradient was 24.0° C km^{-1} or slightly higher (Tanikawa et al., 2016).

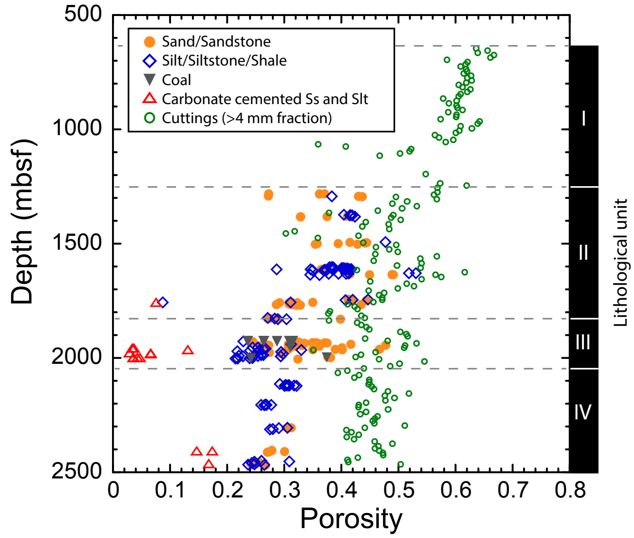

Figure 3. Distribution and lithological variation of porosity in discrete core samples with comparison of cuttings at Site C0020 (Inagaki et al., 2012; Tanikawa et al., 2016). Note that discrete core samples can be more representative for in situ porosity than porosity of cuttings.

5.4 Microbiology and biogeochemistry

Expedition 337 was the first riser-drilling expedition to incorporate extensive on-board microbiological and biogeochemical analyses. All microbiological samples for the cell count, cultivation, and molecular studies were obtained from the center of non-disturbed whole-round core samples after inspection by X-ray CT scan and perfluorocarbon tracer assays for contamination from drill fluids (see Lever et al., 2006; Inagaki et al., 2012) immediately after core recovery. The samples were then processed with special aseptic care in either the microbiology laboratory on the *Chikyu* or the JAMSTEC Kochi Institute for Core Sample Research. Since the target sedimentary habitat is strictly anaerobic, all the cored materials recovered on board were immediately processed for shipboard and shore-based microbiological analyses under the N_2-flushed anaerobic condition. For the composition of gases above, in and below the coalbed, about one million discrete data points could be continuously recorded by mud gas monitoring during riser-drilling operation. Mud gas mon-

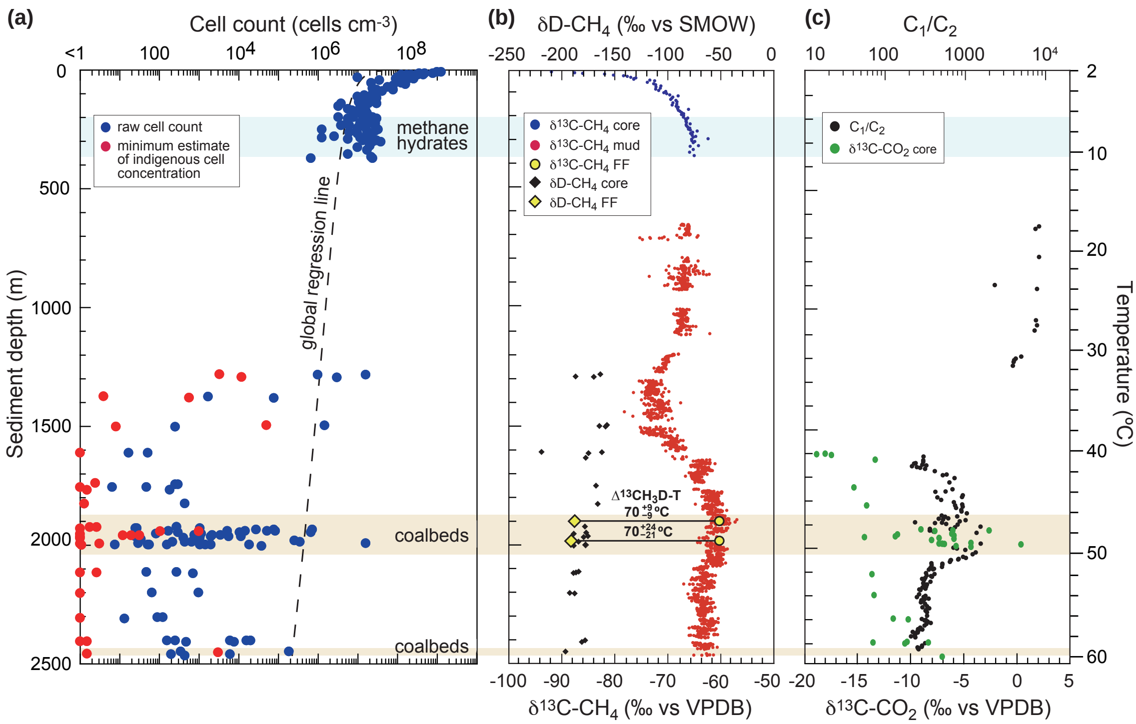

Figure 4. Depth profiles of **(a)** microbial cell concentrations, **(b)** $\delta^{13}C$ and δD of methane, and **(c)** C_1 / C_2 ratios and $\delta^{13}C$ of CO_2 at Site C0020 (Inagaki et al., 2015). Raw data of fluorescence image-based cell counts and the minimum estimates of indigenous cell concentrations corrected for contamination based on molecular data are shown by blue and red symbols in **(a)**, respectively. The minimal quantification limit for raw cell counts was 1.43×10^2 cells cm^{-3}; i.e., the upper 95 % confidence interval of negative background. All $\delta^{13}C$ and δD in **(b)** and **(c)** are in ‰ versus Vienna Pee Dee belemnite (VPDB) and Standard Mean Ocean Water (SMOW), respectively. The $\Delta^{13}CH_3D$–T values designate the apparent equilibrium temperatures derived from measurements of a clumped isotopologue of methane ($^{13}CH_3D$) in discrete formation fluid (FF) samples obtained using the QuickSilver MDT-Probe in situ. Temperature in **(c)** is based on the temperature gradient of 24.0 °C km^{-1} determined by downhole logging. Cell concentration and $\delta^{13}C$ of methane in the upper sedimentary sequence (0–365 m b.s.f.) were obtained at the same location during the JAMSTEC *Chikyu* shakedown expedition CK06-06 in 2006. This figure is slightly modified from Fig. 1 in Inagaki et al. (2015), and reprinted with permission from AAAS.

itoring was supplemented by gas analysis in more than 100 samples from cuttings and cores.

Within the lithological setting of the Shimokita coalbed biosphere, where environmental conditions changed drastically after shallow coastal sediments subsided below sea-level since the Miocene, we have detected the most deeply buried microbial communities studied to date (Inagaki et al., 2015). Microbial cells were detached from sediments by a multi-layer density gradient technique (Morono et al., 2013), and then their concentration was determined by both manual and computer-based microscopic image analyses (Morono et al., 2009, 2013; Morono and Inagaki, 2010). The cell count analysis revealed that cell concentrations in deep sediments below ~ 1.5 km b.s.f. were drastically lower than those predicted by the slope of the global regression line; concentrations typically ranged from ~ 10^2 to 10^3 cells cm^{-3} with local peaks in coal-bearing horizons (Fig. 4a). These extremely low cell concentrations, which are even lower than those in ultra-oligotrophic sediments of the South Pacific Gyre (D'Hondt et al., 2015), suggest that our drilling operations have approached the lower boundary of the deep subseafloor biosphere at this site. Despite the very low cell concentrations, microbial formation of methane via CO_2 reduction was indicated by isotopic data of methane and carbon dioxide (Fig. 4b and c), methanogenic biomarkers, cultivation, and gas composition results throughout the entire drilled sedimentary sequence (Inagaki et al., 2015). The occurrence of in situ methanogenesis was further demonstrated by the successful cultivation of methanogenic microbial communities using an anaerobic bioreactor at 40 °C (Fig. 5); the resulting enrichments include hydrogenotrophic methanogens closely related to *Methanobacterium subterraneum*. Direct biomarker evidence for the activity of methanogenesis in ~ 2 km deep coalbeds is also provided by the detection of intact coenzyme F_{430} in core samples, which is an essential biomolecule in methanogenesis pathway. Moreover, in situ production of methane is supported by measurements of a multiply substituted clumped isotopologue ($^{13}CH_3D$) in methane extracted from in situ formation fluids obtained by using the Schlumberger's QuickSilver MDT-Probe, suggest-

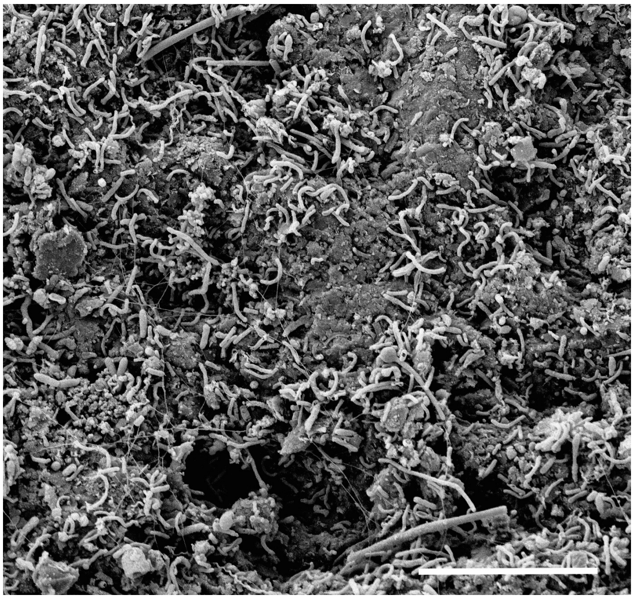

Figure 5. A scanning electron micrograph of an anaerobic, methanogenic microbial community enriched in ~ 2 km deep subseafloor coal samples. The cultivation experiment was carried out using a continuous-flow bioreactor at 40 °C for 694 days. Bar: 10 µm. (Photo: Hiroyuki Imachi, JAMSTEC)

ing clumped-isotope equilibrium temperatures for biogenic methane at ~ 70 °C, which are notably lower than those observed for thermogenic methane in excess of 150 °C (Stolper et al., 2014; Wang et al., 2015).

By comparison of 16S rRNA gene sequences (i.e., V1–V3 region) from control samples to those derived from experimental samples, we determined the taxonomic composition of indigenous bacterial communities. The data indicated that deep bacterial communities (1278–2458 m b.s.f.) differ profoundly from communities at shallower depths (0–364 m b.s.f.) (Fig. 6). For example, no or very low proportions of sequence reads affiliated with the phyla Chloroflexi or "Atribacteria", both globally abundant groups in subseafloor sediments on ocean margins (Inagaki et al., 2003, 2006), were detected in the deep layers. Instead, the sequence assemblage in deep layers is represented, in decreasing order of abundance, by the genera *Alishewanella*, *Patulibacter*, *Thiobacillus*, *Gemmatimonas*, *Actinomycetospora*, *Spirosoma*, *Terriglobus*, and the phylum *Tenericutes* relatives, most of which are heterotrophic bacteria commonly found in forest soils or organic-rich freshwater environments (Inagaki et al., 2015; Fig. 6).

The samples and data from Site C0020 offer the unique opportunity to explore the lower margins of the habitable zone, i.e., the bottom of the deep biosphere, and to search for clues regarding physical, chemical, and bioenergetic factors that limit microbial life below ~ 1.5 km b.s.f. at Site C0020. Physical factors such as low porosity and permeability may influence fluxes of water, nutrients, and metabolic products in the deeply buried sediments at Site C0020. In addition, an important factor controlling the extent of microbial communities could be the increase in energy expanded on the repair of biomolecules. Substantial increases in both modeled biomolecule-damaging rates (abiotic amino acid racemization, DNA depurination) coincide with a sharp drop in cell concentrations at Site C0020 (Fig. 7). Possibly, the increased energetic cost of biomolecule repair results in a higher demand of water and energy for the damage fixation and/or new biosynthesis (Lever et al., 2015), explaining why the environment explored during Expedition 337 appeared to be situated close to the lower boundary of the deep subseafloor biosphere.

Taken together, the major goals of the on-board geology, microbiology, and biogeochemistry programs were successfully accomplished, and extensive shore-based studies using samples and data collected during Expedition 337 will significantly expand our knowledge of the deep, dark, and old subseafloor biosphere and contribute to the better understanding of the biogeochemical carbon cycle.

6 Technical advances

During Expedition 337, our major operational objectives to meet the scientific goals have been successfully accomplished through use of the riser-drilling system of the *Chikyu*. The bottom depth of Hole C0020A is 2466 m b.s.f., extending the previous maximum penetration depth in scientific ocean drilling by 355 m and providing evidence of subseafloor life in the deepest samples retrieved to date. The new on-board facilities such as the mud gas-monitoring laboratory and the radioisotope laboratory were successfully implemented and strongly contributed to the success of Expedition 337. This first deep riser drilling expedition exploring deep life had important strategic value in that this was the first time that the impact of commercially used drilling technology was rigorously tested by a large team of microbiologists, geochemists, sedimentologists, physical property and logging specialists in order to evaluate its compatibility with the scientific goals. Whereas contamination control has become an integral measure of quality assurance in ODP/IODP expeditions with focus on subseafloor life, the riser drilling procedure applied during Expedition 337 required a more rigorous quality assurance/quality control program. As a result, a number of recommendations related to the future use of this technology in scientific ocean drilling can be made.

6.1 Coring technology

During Expedition 337, we performed spot coring, instead of conventional sequential coring strategy, using standard 8 1/2″ RCB coring and 10 5/8″ LDC system. Both coring systems resulted in cores of excellent quality, including very hard carbonate-cemented nodules and conglomerates, from scientifically significant horizons. This spot-coring strategy

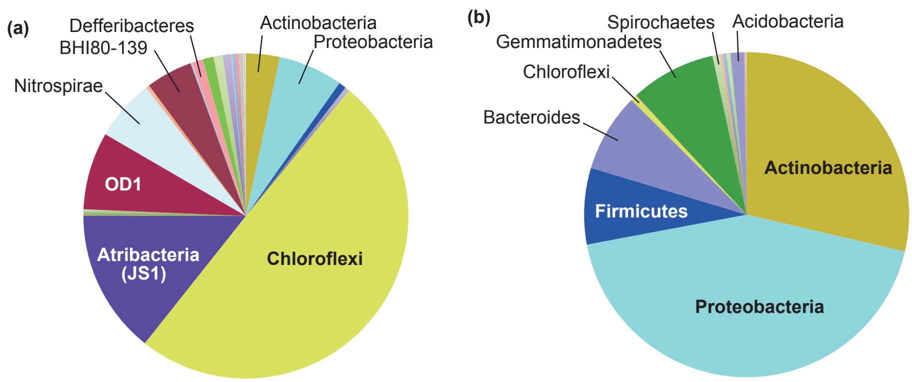

Figure 6. Taxonomic composition of indigenous bacterial communities based on 16S rRNA gene sequences from **(a)** shallow (five samples from 0 to 365 m b.s.f.; a total of 95 179 sequence reads) and **(b)** deep (49 samples from 1.2 to 2.5 km b.s.f.; a total of 5957 sequence reads) sediment samples at Site C0020. This figure is slightly modified from Fig. S3 in Inagaki et al. (2015), and reprinted with permission from AAAS.

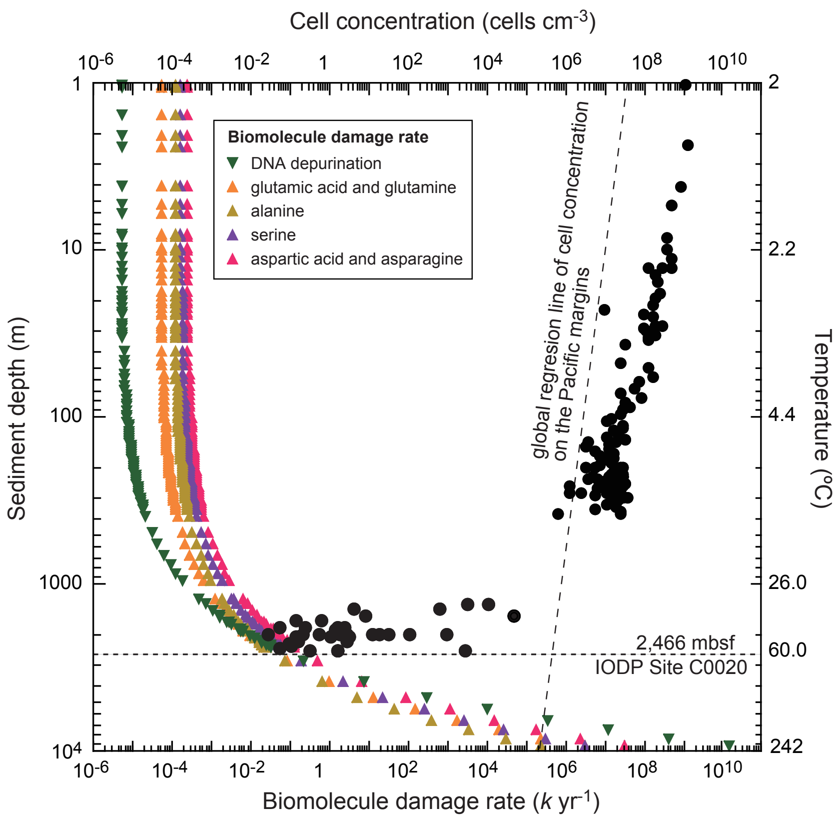

Figure 7. Depth profiles of cell concentrations (black plots), biomolecule damage rates, and in situ temperature at Site C0020. This figure is slightly modified from Fig. S14 in Inagaki et al. (2015), and reprinted with permission from AAAS.

is essential for reducing the cost and time for scientific riser-drilling operation. LDC cores maximize the probability to obtain non-contaminated massive core samples that are adequate for high recovery of pore water, allowing highly sensitive and specific biogeochemical and microbiological analyses. However, the use of an aluminum core liner required modification of the normal workflow and resulted in much longer time requirements for delivery of core material from the rig floor to the laboratory. Nevertheless, we processed LDC cores under anaerobic conditions and retrieved useful data and samples with relatively low levels of contamination for shipboard and shore-based analyses. Considering the high risk of drill mud and microbial contamination of the standard RCB core, it would be desirable to explore the potential use of improved LDC-type coring systems with non-metal core liner (e.g., glass fiber, carbon-reinforced plastic) as the standard spot-coring tool for future deep scientific drilling on the *Chikyu*.

6.2 Drilling mud composition and sterilization

The use of riser-drilling mud is essential for future deep scientific explorations. However, we will need to address both microbial and chemical contamination issues in order to optimize conditions for the examination of very deeply buried microbial communities and the chemical conditions in their habitat. For example, the mud used during Expedition 337 contained about 10^8 contaminant cells mL^{-1}, even though the fluid is alkaline and contains sterilizing chemicals. This high concentration of nonindigenous cells complicated precise detection of indigenous microbial life and its metabolic activities, and hampered the analysis of the chemical composition of pore water. To minimize the risk of drilling mud-related sample contamination during future scientific riser-drilling expeditions, alternative drilling mud compositions (e.g., higher pH) should be considered. For example, are there feasible technologies for mud sterilization that could be implemented without conflicting with operational demands for the deep drilling; can the organic additives that appear to nourish microbial communities be substituted with inorganic components? Can we develop in situ sampling devices for recovering non-contaminated and biologically pristine core and fluid samples?

6.3 Use of deep-riser holes for experiments

A positive aspect of the deep-riser drilling is the superior borehole stability supported by the use of high-viscosity mud that prevents possible collapse and flow-down of rubbly horizons such as coal and fault layers. This is not only useful for coring materials with high recovery rate, but also essential for successful completion of multiple deployments of logging tools, including downhole in situ fluid sampling and analysis by the QuickSilver MDT-Probe. With the combined use of borehole observatory sensors and subseafloor laboratory equipment, the maintenance of stable deep-riser boreholes will be highly useful for advanced subseafloor research in short- to long-term projects.

Last but not least, our expedition also provided a test ground for the use of riser-drilling technology to address geobiological and biogeochemical objectives and was therefore a crucial step toward the next phase of deep scientific ocean drilling. Since the riser system was originally developed by the petroleum industry, the *Chikyu* is equipped with a mature technology. However, the adaptation of this technology to the needs of basic science will be an important challenge that needs to be addressed as integral component in plans for the next riser missions. Implementation of "science-oriented" deep-riser drilling for high-quality samples would provide grand opportunities for Earth system sciences.

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Scientific Drilling
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Science Reports

The Towuti Drilling Project: paleoenvironments, biological evolution, and geomicrobiology of a tropical Pacific lake

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Abstract. The Towuti Drilling Project (TDP) is an international research program, whose goal is to understand long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediments through the scientific drilling of Lake Towuti, southern Sulawesi, Indonesia. Lake Towuti is a large tectonic lake at the downstream end of the Malili lake system, a chain of five highly biodiverse lakes that are among the oldest lakes in Southeast Asia. In 2015 we carried out a scientific drilling program on Lake Towuti using the International Continental Scientific Drilling Program (ICDP) Deep Lakes Drilling System (DLDS). We recovered a total of ∼1018 m of core from 11 drilling sites with water depths ranging from 156 to 200 m. Recovery averaged 91.7 %, and the maximum drilling depth was 175 m below the lake floor, penetrating the entire sedimentary infill of the basin. Initial data from core and borehole logging indicate that these cores record the evolution of a highly dynamic tectonic and limnological system, with clear indications of orbital-scale climate variability during the mid- to late Pleistocene.

1 Introduction

The Towuti Drilling Project (TDP) is an international research program, whose objective is to understand long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediment. To accomplish this goal, the TDP recovered over 1000 m of sediment core from the floor of Lake Towuti, the largest tectonic lake in Southeast Asia. Analysis of these cores is just beginning, but will provide a new long, high-resolution record of tropical western Pacific paleohydrology during the Pleistocene, information on the age and history of the lake and the limnological conditions that gave rise to Towuti's endemic fauna and flora, and new insight into the microbial processes operating at depth in Towuti's sediments and their effects on sediment mineralogy and biogeochemistry.

Lake Towuti is a large tectonic lake at the downstream end of the Malili lake system (Fig. 1), a set of five ancient, tectonic lakes that have formed over the past ∼1.5 million years on the island of Sulawesi, Indonesia (Haffner et al., 2001; Lehmusluoto et al., 1995; Russell and Bijaksana, 2014). These are the oldest lakes in Indonesia and are thought to contain the longest continuous terrestrial records of climate in the Indo-Pacific Warm Pool (IPWP), a vast pool of warm surface waters in the western tropical Pacific. The IPWP exerts enormous influence on global climate through its interactions with the El Niño–Southern Oscillation (ENSO), the Australasian monsoons, and the Intertropical Convergence Zone (ITCZ) (Chiang, 2009; Clement et al., 2001; Seager and Battisti, 2007) and through its influence on the concentration of atmospheric water vapor – the Earth's most important greenhouse gas (Pierrehumbert, 1999, 2000). Our ability to make accurate predictions about future climate, and in particular future precipitation, thus rests on our understanding of the tropical Pacific climate under different climate boundary conditions than today. Global climate models exhibit significant inter-model differences in their simulations of recent and future precipitation change over the IPWP (Kumar et al., 2013; Meehl et al., 2007), as do simulations of IPWP precipitation under glacial boundary conditions (DiNezio et al., 2011; DiNezio and Tierney, 2013), motivating scientific drilling at Lake Towuti.

In recent years the global lakes drilling program under the auspices of the International Continental Scientific Drilling Program (ICDP) has made substantial contributions to understanding Pliocene–Pleistocene climate variability, including multiple paleoclimate records from the northern and southern tropics. These records, together with many long speleothem data sets, have highlighted the importance of 21 000-year cycles in subtropical rainfall, indicating strong forcing of the strength of the monsoons by orbital precession (e.g., Fritz et al., 2007; Hodell et al., 2007; Scholz et al., 2007; Wang et al., 2008). Despite these advances, we lack long records of terrestrial paleoclimate from equatorial regions and particularly the Indo-Pacific. Previous sedimentary records from Lake Towuti span the last ∼60 kyr BP, and contain an intriguing record of past climate that differs markedly from that of the subtropics (Russell et al., 2014). In particular, we observed grassland expansion, lowered lake levels, and strong drying during the last glacial maximum (LGM) relative to both marine isotope stage 3 (∼30–60 kyr BP) and the Holocene (Costa et al., 2015; Konecky et al., 2016; Russell et al., 2014; Vogel et al., 2015). The strong glacial–interglacial signal at Lake Towuti challenges the hypothesis that tropical hydroclimate is predominantly controlled by precessional orbital forcing, with little influence of glacial–interglacial changes in climate boundary conditions (Carolin et al., 2013; Meckler et al., 2012). A critical goal of TDP is, therefore, to obtain a continuous sedimentary record to document orbital-scale patterns of climate change spanning as many glacial–interglacial cycles as possible to test and differentiate the forcings that govern Indo-Pacific rainfall variations.

Lake Towuti is not simply a repository of information on past climate. The lake is situated within the East Sulawesi Ophiolite (Fig. 1; Kadarusman et al., 2004; Monnier et al., 1995), the third largest ophiolite in the world, which releases iron, chromium, and other metals that catalyze biogeochemical activity by a unique and diverse microbial community in the lake and its sediments (Crowe et al., 2008). Lake Towuti's

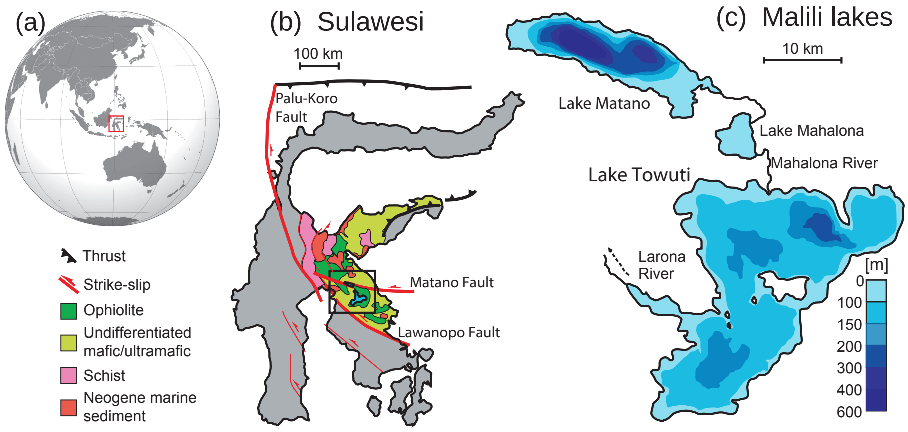

Figure 1. Overview map of the study area showing **(a)** the location of Sulawesi in the Indo-Pacific region, **(b)** the regional geology of Sulawesi (modified after Kadarusman et al., 2004), and **(c)** the configuration of the Malili lake system.

sediments are extremely Fe rich and thus stand out as an end-member microbial habitat. The prevalence of Fe-rich sedimentary rock units in the Precambrian suggests that ferruginous conditions were a prominent feature of the deep ocean throughout the Earth's history (Poulton and Canfield, 2011), and with mounting evidence for Fe-rich Martian soils and lake sediments dominated by ultramafic weathering products (e.g., Ehlmann et al., 2008), the study of an active biosphere in environments such as Towuti is timely and critical. Moreover, Towuti's pelagic microbial ecology, biogeochemistry, and sediment mineralogy are tightly linked to climate variations through varying lake mixing regimes, soil erosion, and weathering (Costa et al., 2015; Tamuntuan et al., 2015). These processes are directly or indirectly responsible for the production and deposition of many paleoclimate proxies, and postdepositional alteration of those proxies is often linked to the activity of sedimentary microorganisms. In light of these issues, a critical component of the TDP is to investigate the microbial community at depth and its effects on iron mineralogy, carbon, and metal cycling using a variety of state-of-the-art geochemical, molecular genetic, and isotopic tools.

Towuti is surrounded by one of the most diverse tropical rainforests on Earth, and harbors endemic species flocks of fish, snails, shrimp, crabs, and other organisms. Identifying the role of past environmental change in governing the evolution and biogeographical range of these organisms will be crucial for identifying conservation priorities and strategies to cope with anthropogenic climate change and land use. In terms of its flora, Sulawesi lies within one of the world's most biologically complex and diverse regions and is home to fundamentally important faunal and floristic boundaries such as the famed Wallace Line (which separates fauna of Australian and Asian origin). The regional phytogeography is controlled by these diverse geological origins and by subsequent modification by climate variations, particularly the glacial–interglacial cycles, which have influenced the connectivity between adjacent islands as well as drought tolerance and resilience of the regional flora (Cannon et al., 2009; van Welzen et al., 2011). Understanding the past dynamics of these forest communities therefore is critical for our understanding of their response to future change. Faunally, the Malili lakes offer by far the most outstanding example of lacustrine biological evolution in Southeast Asia, with parallel adaptive radiations of gastropods (Rintelen et al., 2004), crabs (Schubart et al., 2008), shrimps (Rintelen et al., 2010), and fishes (Herder et al., 2006). Genetic and morphological data indicate multiple colonizations of the lakes in several of these groups; a high level of endemism within each lake, suggesting allopatric speciation despite the presence of riverine connections among the lakes; and intralacustrine diversification through shifting trophic structure suggesting ecological speciation (Rintelen et al., 2012). These faunal data thus have strong links to the climatic, limnological, and geological evolution of Lake Towuti. Drilling in Lake Towuti will document the environmental and climatic context that shaped the evolution of these unique lacustrine and terrestrial ecosystems, and their resilience to long-term environmental change.

These outstanding characteristics motivated the TDP, under the auspices of the ICDP. Through continuous coring of the entire sedimentary sequence of Lake Towuti, the project aims to

1. reconstruct long-term hydrologic change in central Indonesia in order to understand the processes controlling long-term climate change in the tropical western Pacific;

2. discover the micro-organisms living in Towuti's metal-rich sediments, and determine their impacts on the lake's sediments and biogeochemistry;

3. evaluate the history and stability of Sulawesi's lush rainforests, and the impacts of past climate change on these ecosystems;

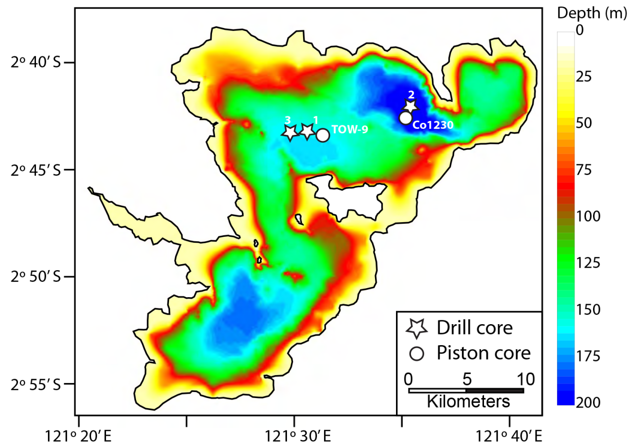

Figure 2. A bathymetric map of Lake Towuti showing the location of core sites discussed in the text.

4. document the age of Lake Towuti, its long-term limnological history, and the environmental background shaping the diversification of Towuti's endemic flora and fauna.

2 Study site

Lake Towuti is located near the Equator (2.75° S, 121.5° E; Figs. 1 and 2) at 318 m above sea level in central Sulawesi, Indonesia. The island of Sulawesi has a complex tectonic history. At the large scale, a complex zone of deformation extends across central Sulawesi and absorbs the collision of Australia with Asia (Sundaland). Three major sinistral strike-slip fault systems accommodate this motion: the Palu-Koro, Matano, and Lawanopo faults. Lake Towuti and neighboring lakes occupy small transtensional basins along the Matano Fault. Northeast of Sulawesi, the Molucca Sea subduction zone accommodates convergence between the Philippine Sea Plate and Sundaland, giving rise to extensive volcanic fields in northern Sulawesi (Hamilton, 1988).

Sulawesi is composed of four elongate "arms", which broadly correspond to lithotectonic units (Hamilton, 1979). The southeast arm, which houses Lake Towuti, is dominated by the highly tectonized East Sulawesi Ophiolite, which is inter-thrust with Mesozoic and Cenozoic sediments. These rocks are comprised of ultramafic mantle peridotites (lherzolites and harzburgites), cumulate gabbros, and basalts of normal mid-ocean ridge composition (Kadarusman et al., 2004; Monnier et al., 1995). The ophiolites have sourced large lateritic nickel deposits that have attracted the mining industry since the beginning of the 1970s, with active operations and extensive infrastructure in the region currently operated by PT Vale Indonesia (a subsidiary of Vale SA).

The three largest of the Malili lakes, Matano, Mahalona, and Towuti, are connected with surface outflow from Matano to Mahalona to Towuti via the Mahalona River, the largest river inflow to the lake (Fig. 2). Lake Towuti is the largest of the Malili lakes, with a surface area of 560 km^2 and a maximum water depth of 200 m (Haffner et al., 2001; Lehmusluoto et al., 1995). A chain of islands divides the lake into two basins: a larger northern basin that contains the deepest part of the lake, and a smaller southern basin. Lake Towuti is presently hydrologically open with outflow to the southwest through the Larona River, which flows to the Bay of Bone.

Lake Towuti experiences a tropical humid climate. The region receives ~ 2700 mm yr^{-1} of precipitation, with a wet season from December–May, during which strong northeasterly flow, warm sea surface temperatures (SSTs), and local convective activity (Hendon, 2003) maintain precipitation at > 250 mm $month^{-1}$. Precipitation falls below 150 mm $month^{-1}$ from August–October, when southeasterly flow and cool SSTs suppress regional convection. This circulation and precipitation seasonality is characteristic of much of southern Sumatra, southern Borneo (Kalimantan), Java, and the Moluccas (Hendon, 2003), suggesting our record should represent climate change across a broad swath of central and southern Indonesia (Aldrian and Susanto, 2003; Konecky et al., 2016).

Towuti's surface water temperatures vary between ~ 29 and 31° C. The lake water column is thermally stratified, with seasonal mixing to a depth of ~ 100 m (Costa et al., 2015). Lake Towuti is relatively dilute (210 µS cm^{-1}) and circumneutral (pH ~ 7.8) with a chemistry dominated by Mg and HCO_3^- (Haffner et al., 2001; Lehmusluoto et al., 1995). The lake is among the least productive tropical lakes on Earth (ultraoligotrophic), likely due to low nutrient delivery from intensely weather soils and sedimentary PO_4^{3-} trapping by very high Fe concentrations. The surface waters are well-oxygenated, but hypoxic to anoxic conditions exist below ~ 120 m depth allowing for the development of ferruginous conditions with very low concentrations of dissolved sulfur.

3 Core site selection

Site selection for the TDP was guided by three surveys carried out between 2007 and 2013 that collected over 1000 km of seismic reflection data and piston cores that document the nature of the upper 10–20 m of Towuti's sediment column. Seismic data include "CHIRP" data acquired with an Edgetech™ 216s Towfish with a topside 3200XS collection system, and both single channel and multichannel data collected using a Bolt™ 5 in^3 airgun and a 150 m long Geometrics™ GeoEel solid digital streamer with 24 channels.

The seismic data revealed two major sedimentary units in Lake Towuti (Fig. 3; Russell and Bijaksana, 2012). Unit 1 consists of a well-stratified sequence that extends from the lake floor down to ~ 100 m sub-bottom, and is characterized by parallel acoustic reflectors that can be traced across most of the basin. These reflectors do not exhibit obvious geomet-

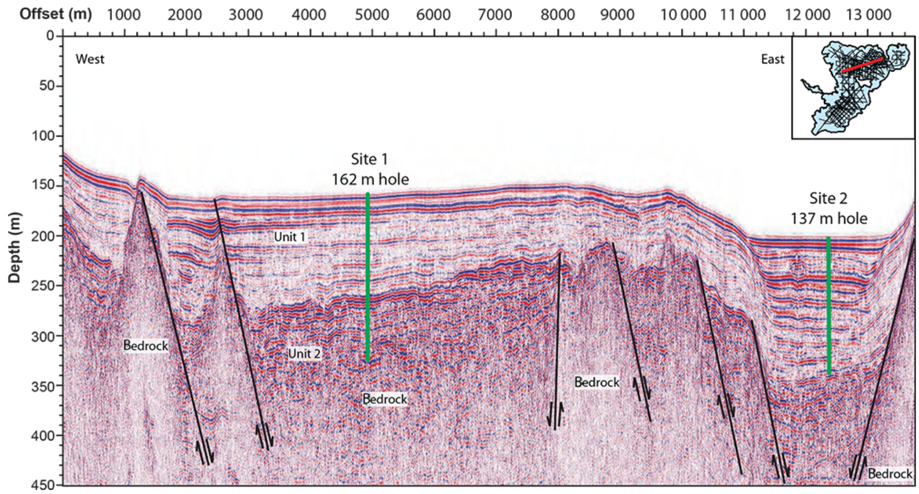

Figure 3. Seismic reflection profile oriented WSW–ENE over Lake Towuti's northern basin (see inset for line position) crossing TDP Sites 1 and 2. Thick green lines show the borehole depths for TDP-TOW15-1B and TDP-TOW15-2A. Seismic Units 1, 2, and bedrock are labeled, and major faults are indicated by thin black lines.

ric relationships such as angular contacts that would indicate large lake-level changes, suggesting stable, continuous, fine-grained sediment deposition in Towuti's deep basins. Some of the thickest Unit 1 accumulations are found in the deepest basin of Lake Towuti, located near the northern shore of the lake. This basin receives distal deltaic sediments derived from the Mahalona River, which drains the upstream lakes Matano and Mahalona.

Our piston coring survey sampled only the uppermost sediments of Unit 1, but confirmed the observations from our seismic reflection data. A core collected at site TOW-9 (Fig. 2) documented continuous, fine-grained sedimentation in the central part of Towuti's northern basin, with sedimentation rates of $\sim 5.5\,\mathrm{kyr\,m^{-1}}$ during the past ~ 60 kyr BP (Russell et al., 2014). We found very frequent distal deltaic turbidites in the deepest part of the lake (Site Co1230, Fig. 2), particularly during lake-level low stands that remobilize delta topset beds and force deltaic progradation (Vogel et al., 2015). Elsewhere, the piston cores generally consisted of fine-grained clays interbedded with more or less frequent turbidites. Turbidites increased in frequency and thickness with proximity to the Mahalona River delta, but were also common near shorelines or in the deepest parts of sub-basins within the lake, perhaps originating from seismically induced failure of poorly consolidated sediments in this tectonically active basin.

Unit 1 is underlain by Unit 2, a more poorly stratified unit that varies between a few tens to ~ 150 m in thickness. Unit 2 is characterized by a range of sediment types, from continuous, sub-parallel reflectors to short, discontinuous reflectors. Prior to drilling, Unit 2 was interpreted to reflect alternating fluvial and lacustrine sedimentation that occurred during the initial stages of formation of Lake Towuti. Drilling Unit 2 could provide insight into Lake Towuti's age, processes of basin formation, and the early lake stages, which is information critical to understanding the biological evolution of Towuti's endemic fauna.

Based upon these data, we selected three primary drilling sites, between 156 and 200 m water depth, and with drilling targets between ~ 130 and ~ 175 m sub-bottom. Our primary goals in selecting drilling sites were to recover

1. high-quality continuous sections with as few turbidites as possible through Unit 1 for paleoclimate, paleolimnological, and geomicrobiological studies;
2. a distal record of the Mahalona River system to monitor changes in deltaic sedimentation forced by lake-level changes and possible changes in the river system itself signaling changes in the hydrological connectivity of lakes Towuti, Mahalona, and Matano;
3. as long a section as possible through Unit 2, preferably at sites containing more lacustrine than fluvial sedimentation (fine-grained deposits).

Site 1 is TDP's primary drilling target, located in the central part of Towuti's northern basin in ~ 156 m water depth (Fig. 4a). This "master site" is located close to our piston coring site TOW-9, which has yielded high-quality paleoclimatic and paleolimnologic reconstructions. The site is located upslope of slightly deeper areas of the lake on the northern edge of Loeha Island, and south of a large WNW–ESE trending intrabasin fault that limits sediment inputs from the Mahalona River, and thus contains few turbidites. Site 1 is well-suited to address most of our key studies in paleoclimate, paleolimnology, paleoecology, and geomicrobiology. Seismic data over Site 1 show that Unit 1 is approximately 100 m thick, and piston cores suggest the site is undisturbed

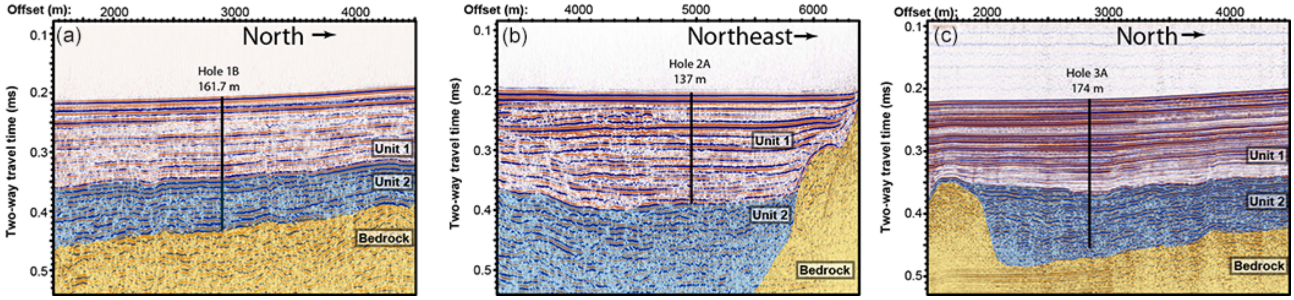

Figure 4. Expanded seismic reflection sections over the TDP core Sites 1 **(a)**, 2 **(b)**, and 3 **(c)**, with seismic Units 1 and 2, and bedrock labeled. Black lines show the positions and depths of TDP-TOW15-1B, TDP-TOW15-2A, and TDP-TOW15-3A.

by turbidites or other event deposits. Seismic data also imaged approximately at least 75 m of sediment in Unit 2, including two intervals marked by roughly parallel acoustic reflectors centered at ~ 115 and ~ 160 m depth, indicating relatively well-stratified sediments. Our primary goals at Site 1 were to obtain overlapping triplicated cores through the upper ~ 100 m, to obtain 100 % recovery of Unit 1, and to recover as complete a section as possible of Unit 2 including cores to bedrock if possible.

Site 2 is located in the deepest part of Lake Towuti at 200 m water depth (Fig. 4b). Piston core Co1230 indicates that this site receives distal deltaic sediments derived from the Mahalona River, and seismic reflection data indicated a major change in the acoustic character of the sediments at ~ 65 m depth that could reflect the beginning of distal deltaic sedimentation from the Mahalona River. The principle objectives of drilling this location were therefore to provide a record of lake-level changes and/or major changes in the hydrological connection between lakes Towuti, Mahalona, and Matano through study of these distal deltaic deposits. Changes in the amount and style of clastic sedimentation, together with sediment provenance studies, at Site 2 may provide relatively direct insight into the history of hydrological connectivity between the Malili lakes, with important implications for the biological, hydrological, and geological evolution of Lake Towuti. Seismic reflection data suggested ~ 130 m of well-stratified lacustrine sediment at this site, so our goal was to recover duplicate overlapping cores to the Unit 1–Unit 2 boundary.

Site 3 was originally proposed for Towuti's southern basin to provide a sedimentary sequence unaffected by sedimentological changes associated with the evolution of the Mahalona River, in order to test the reproducibility of our reconstructions of terrestrial weathering and sediment supply obtained from Site 1. The long transit times to Towuti's southern basin, combined with equipment failures, forced us to relocate Site 3. An alternate site was selected to the west of Site 1 in 159 m water depth (Fig. 4c). Seismic data suggested that this site could have the most continuous lacustrine sedimentation through the time period represented by Unit 2, as the site is located in a small structural sag that may have allowed for continuous lacustrine conditions while other sites in the basin were dry. Our goal at this site was to obtain overlapping duplicated cores as deeply as possible.

4 Drilling, logging, and on-site geomicrobiological operations

Drilling in a remote part of central Indonesia was a difficult logistical undertaking. Major logistical activities began in September 2014, when we shipped 14 containers of drilling equipment and supplies from the United States of America to the town of Sorowako, Sulawesi Selatan, Indonesia; initiated research permit applications and paperwork; began on-site construction of a dock and crane pad from which we could launch the drilling barge; and developed agreements with PT Vale Indonesia for local logistical support including the use of cranes, housing, and assistance with environmental, health, and safety planning. We shipped the GFZ "Buglab" to Sorowako to support on-site sample processing for geomicrobiological investigations, as well as borehole logging equipment from the Leibniz Institute for Applied Geophysics (LIAG), Hanover, Germany. Logistical preparations were completed in May 2015, when the drilling team arrived and set up on-site analytical facilities and the drilling barge on Lake Towuti's shore.

Drilling commenced at Site 1 on 23 May 2015 using the ICDP Deep Lakes Drilling System (DLDS) operated by DOSECC Exploration Services. Boreholes were drilled using PQ (122.6 mm hole, 66 mm core) diameter drill string, which uses the hydraulic piston corer (HPC) for soft sediment and the "Alien" rotating corer to recover more resistant lithologies; attempts to recover more resistant lithologies with the Extended Nose Corer (EXN) resulted in poor core recovery and quality. All cores were recovered into standard butyrate liners. Geophysical downhole logging data, including natural gamma radiation, magnetic susceptibility (MS), electrical resistivity, temperature, acoustic velocity, vertical seismic profiles, and borehole diameter and dip, were measured at varying depth resolutions in a subset of holes.

A multisensor core logger (MSCL; Geotek Ltd.) was used to collect magnetic susceptibility (MS) and p wave veloc-

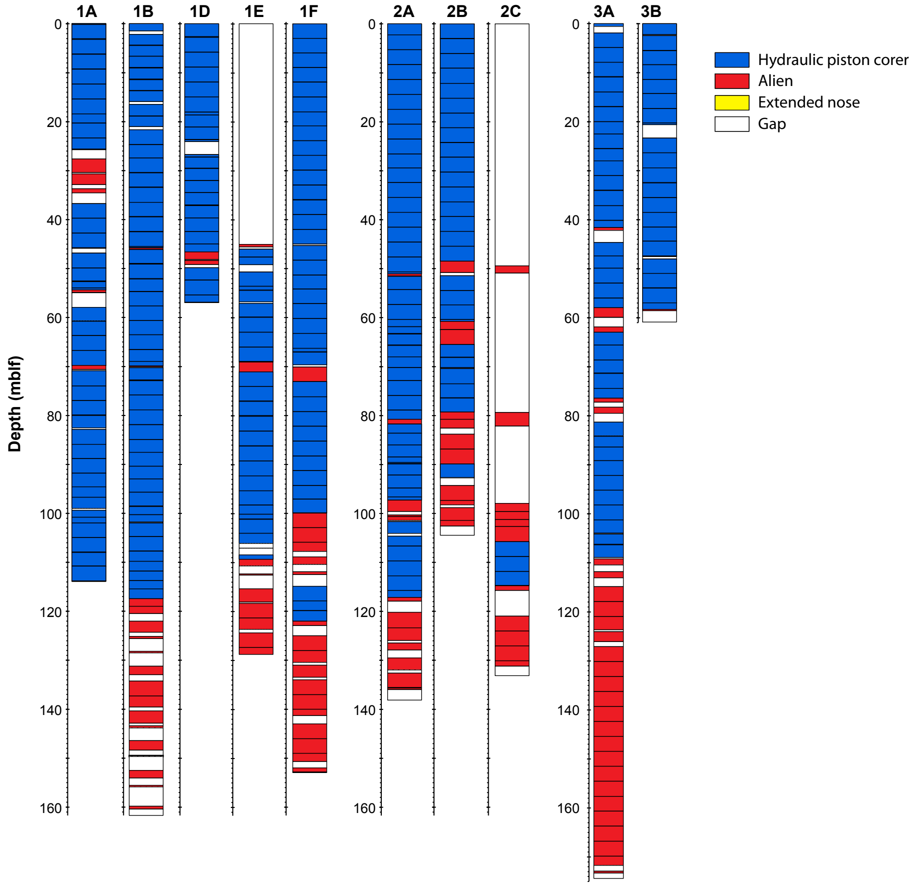

Figure 5. Core recovery from the TDP drill sites in Lake Towuti. Colors indicate the various tools used to recover cores from all TDP sites except 1C. White boxes indicate intervals that were not recovered.

ity data on whole cores in an on-site laboratory immediately after drilling, though the *p* wave velocity data were of low-quality due to gas expansion in most cores. At Hole 1A, also known as the "bughole", a fluid contamination tracer was used to aid geomicrobiological sampling. Samples were collected from cores from Hole 1A immediately upon recovery on the drilling barge to measure trace and redox-sensitive gas concentrations (such as methane), and over 450 samples were subsequently processed in the BugLab for analyses of pore-water chemistry, cell counting and microbial fingerprinting, experiments on microbial turnover and processes, and organic geochemistry.

Upon conclusion of drilling operations, cores were shipped via air freight to LacCore, the National Lacustrine Core Facility at the University of Minnesota, USA, for full processing, description, scanning, and subsampling. There, physical properties for whole cores were analyzed via MSCL-S to obtain *p* wave velocity, gamma density, loop MS, electrical resistivity, and natural gamma radiation data at intervals of 2–4 cm. After splitting, cores were logged using an MSCL-XYZ to obtain high-resolution MS and color reflectance spectrophotometry at 0.5 cm resolution. Split cores were cleaned and scanned with a Geotek™ Geotek Single Track Core Imaging System (MSCL-CIS) digital linescan imager. Visual core description and smear slide analyses were carried out to classify the sediment into major compositional units, and subsamples were extracted at intervals coordinated to obtain stratigraphically equivalent samples for sedimentological, geochemical, and paleoecological parameters. All cores received identical treatment except cores from Hole 1C, which were left in Indonesia to aid in educational and outreach activities, and cores from Hole 1A, many of which were completely sampled in the field leaving no material for logging nor core description.

5 Initial coring and core description results

TDP drilled 11 boreholes in total (Table 1), although several of these were relatively short due to twist offs that broke drilling rods, or other equipment malfunctions. In total we drilled ∼ 1228 m of sediment and recovered ∼ 1018 m of core within the intervals where coring was attempted, resulting in a recovery of 91.7 % (Fig. 5). Recovery was generally very high through the upper ∼ 100 m of sediment (Unit

1), but much lower in Unit 2 due to the presence of coarse-grained unconsolidated lithologies. We acquired borehole logging data from three holes, though not all parameters were logged at all depths due to borehole collapse in shallow unconsolidated sediment. Attempts to collect vertical seismic profiles at Site 1 were unsuccessful due to equipment malfunction, and were not repeated at other sites.

Six boreholes were drilled at Site 1 yielding approximately 524 m of core. Drilling commenced at Site 1A on 23 May 2015, and penetrated ∼ 115 m reaching ∼ 10 m below the Unit 1–Unit 2 boundary. Our geomicrobiology team did extensive sampling of this core in the field. The majority of the core consists of relatively soft clays that were cored with the HPC; however, we encountered four relatively hard beds between ∼ 25 and 70 m sub-bottom that required drilling with the Alien tool. These hard beds were later determined to be tephras, which, despite their deposition as airfall, were frequently semi-lithified. Drilling the soft sediments surrounding these tephras with the Alien tool resulted in significant homogenization and contamination of these cores, as revealed by our contamination tracer, will be published elsewhere. We subsequently adjusted our drilling strategy to maximize recovery of the tephras while minimizing disturbance of the soft clays. Drilling was terminated in this hole upon encountering the first resistant sand bed, in order to start a new hole to ensure duplication of the upper 100 m of the sediment column.

Our second hole, 1B, was our deepest hole at Site 1, extending to 162 m below lake floor (m b.l.f.). The upper ∼ 115 m b.l.f. was very similar to Hole 1A, but the lower ∼ 46 m b.l.f. consisted of a variety of coarser-grained lithologies that resulted in relatively low recovery. Coring was terminated at ∼ 162 m b.l.f. after coring ∼ 0.40 m of bedrock, which consisted of a lithified mafic conglomerate that appears similar to Eocene-aged deposits that occasionally outcrop in the region.

While drilling Hole 1B, we began to experience problems with the hydraulic power system of the drilling rig, and after completing Hole 1B, we completely lost rig function. Drilling operations had to be shut down for 18 days in order to replace the main hydraulic pumps of the rig. We then repositioned the drill rig and cored a short hole, 1C, which extended only ∼ 5.5 m b.l.f. After correcting additional hydraulic problems identified while drilling this hole, we drilled three additional holes at Site 1 (1D, 1E, and 1F). Hole 1D extends ∼ 54 m b.l.f. with excellent recovery, and was terminated due to a stuck tool. We repositioned and reamed to ∼ 45 m b.l.f. with a non-coring assembly (NCA) at Hole 1E, and then cored the interval from 45 to ∼ 129 m b.l.f. with 91 % recovery. In light of the various equipment issues and difficulties recovering sediments around tephras in Unit 1 and coarse sediments in Unit 2, we drilled a sixth and final hole, 1F. This hole extends to ∼ 154 m b.l.f., with nearly 95 % recovery, and was terminated when we encountered gravel that, based on 1B, cap a bedrock–soil–fluvial sequence. Holes 1B and 1F were successfully logged for various geophysical parameters, though barge movement and borehole collapse prevented logging of the upper ∼ 20 m of sediment.

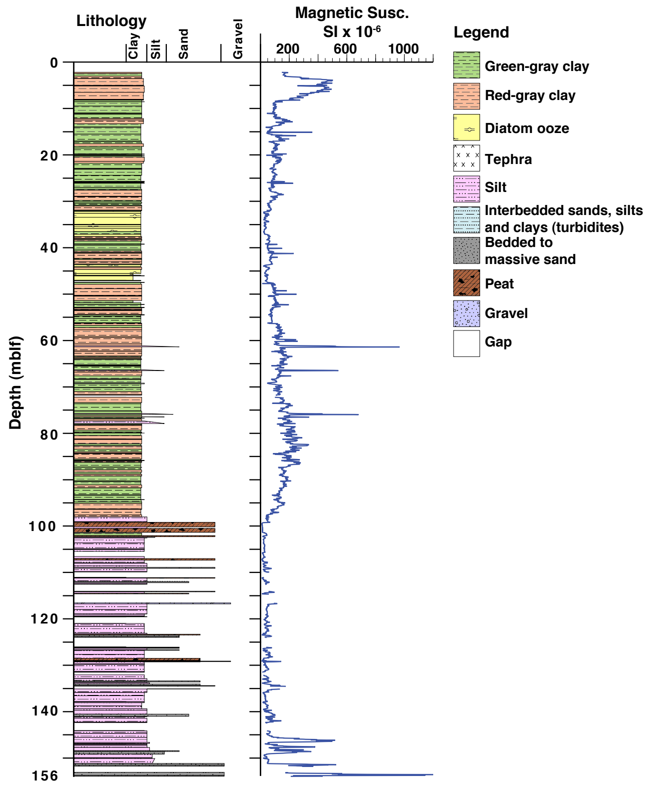

Figure 6. Summary stratigraphy of core TDP-TOW15-1F, based on initial core descriptions. Lithology data are based upon visual and smear slide descriptions, and are rendered in PSICAT. Magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL are shown in the central panel, and at far right is the key to the lithologic symbols. Blank (white) areas indicate zones with no recovery.

Core 1F is the most complete section from Site 1 and its lithology is representative of the section recovered from this site (Fig. 6). The basal sediments consist of a variety of lithologies including alternating gravels, poorly to well-sorted sands, silts, clayey silts, and peats. This unit is capped by a ∼ 2.5 m thick woody peat at ∼ 100 m b.l.f., which correlates to the transition from Unit 2 to Unit 1 in seismic reflection data. The upper 100 m of sediments consist largely of alternating thinly bedded to massive dark reddish-gray to dark-green gray clays. Normally graded silts (turbidites) are relatively rare but more common in the lower ∼ 50 m of this interval, and we discovered ∼ 14 light gray tephras that range from ∼ 1 to ∼ 40 cm thickness and are scattered through the upper ∼ 95 m. The source of these tephras is currently under investigation, but they likely derive from the Tondano caldera system in northern Sulawesi, which is the closest tephra source to Lake Towuti. We also observed two

Table 1. Summary information about TDP drill sites. Drilled depth indicates the bottom depth of each hole; % recovery indicates the meters of core recovered within the depth intervals where coring was attempted, and thus excludes intervals drilled with a non-coring assembly.

Labels	Water depth (m)	Core length (m)	Drilled depth (m b.l.f.)	Recovery (%)	Borehole logging	Remarks
Site 1						
TDP-TOW15-1A	156	105.837	113.58	93.2	N	Geomicrobio Site
TDP-TOW15-1B	156	137.871	161.7	85.3	Y	
TDP-TOW15-1C	156	4.455	5.64	79.0	N	Rig failure
TDP-TOW15-1D	156	53.21	53.91	98.7	N	Ended in twist off
TDP-TOW15-1E	156	76.19	128.72	91.0	N	Continuation of 1D
TDP-TOW15-1F	156	145.965	154.06	94.7	Y	
Site 2						
TDP-TOW15-2A	201	134.515	137.58	97.8	Y	
TDP-TOW15-2B	201	103.918	104.55	99.4	N	Ended in twist off
TDP-TOW15-2C	201	34.175	133.21	82.9	N	Continuation of 2B
Site 3						
TDP-TOW15-3A	159	166.08	174.09	95.4	N	
TDP-TOW15-3B	159	55.3	60.88	90.8	N	Ended in twist off
TOTAL		1017.5	1227.9			

3–5 m thick intervals of laminated to medium-bedded diatomaceous ooze. Diatoms are not a significant part of the pelagic phytoplankton in the present-day lake (Haffner et al., 2001; Lehmusluoto et al., 1995), suggesting that these intervals mark major changes in the biogeochemical functioning of Lake Towuti.

Three holes were drilled at Site 2 to obtain a record of the evolution of the Mahalona River delta. Hole 2A reached ~ 134 m b.l.f. with ~ 98 % recovery, though there was significantly more gas expansion at Site 2 than at Site 1, which contributed significantly to the high apparent recovery. Coring was terminated when we reached sandy gravel, interpreted to correspond to the Unit 1–Unit 2 boundary observed in seismic reflection data (Fig. 4b). Hole 2B extended to ~ 105 m b.l.f., and ended in a twist off of the drilling rod. We repositioned and in Hole 1C reamed down to 100 m using a NCA, with spot coring to close coring gaps in 2A and 2B. We then cored from ~ 100 to ~ 133 m with 83 % recovery.

Hole 2A provides the most complete and representative stratigraphy from Site 2. The upper ~ 71 m of this core consist of 1–80 cm thick normally graded silts (Fig. 7), reflecting deposition by turbidity currents, interbedded with dark reddish to greenish-gray silty clay, whereas the lower 64 m consists largely of alternating thinly bedded to massive dark reddish-gray to dark-green gray clays similar to Site 1. We observe multiple tephra beds as well as two intervals of diatomaceous ooze, similar to Site 1. The tephras are much thicker than observed at Site 1, likely reflecting enhanced reworking of tephra from the Mahalona Delta and steep slopes bordering the basin.

We drilled our deepest hole of the project at Site 3, where Hole 3A reached ~ 174 m b.l.f. with over 95 % core recovery. Drilling at 3A was terminated when we encountered gravel near the contact with bedrock (Fig. 8). We began a second hole, 3B, which ended in a twist-off while trying to drill through a tephra at ~ 61 m depth. Due to time and budgetary constraints, we were not able to drill a third hole at Site 3 and concluded the project. Hole 3A, however, contains an excellent record of sedimentation at this site. Unit 1 at Site 3 is similar to that of Site 1, but is slightly expanded (~ 10 % thicker) and contains much more frequent turbidites, particularly in the lower ~ 50 m. Peats are less common in Unit 2 of Site 3 than at Site 1, and the sediments are generally finer grained, resulting in better recovery. These observations are consistent with our interpretation of the seismic reflection data that places Site 3 in a small structural basin that supported more continuous lacustrine sedimentation during the early stages of formation of Lake Towuti basin.

6 Conclusions

The TDP cores record the evolution of a highly dynamic tectonic and limnological system. Sediments in Unit 2 represent a mixture of lacustrine, fluvial, and terrestrial sediments deposited during the initial stages of extension and subsidence of the Lake Towuti basin. Comparison of Unit 2 sediments between Sites 1 and 3, or even between different holes drilled at Site 1, suggest Unit 2 is highly spatially variable over short distances, perhaps reflecting a variety of lake, swamp, and riverine environments that existed simultaneously in a large,

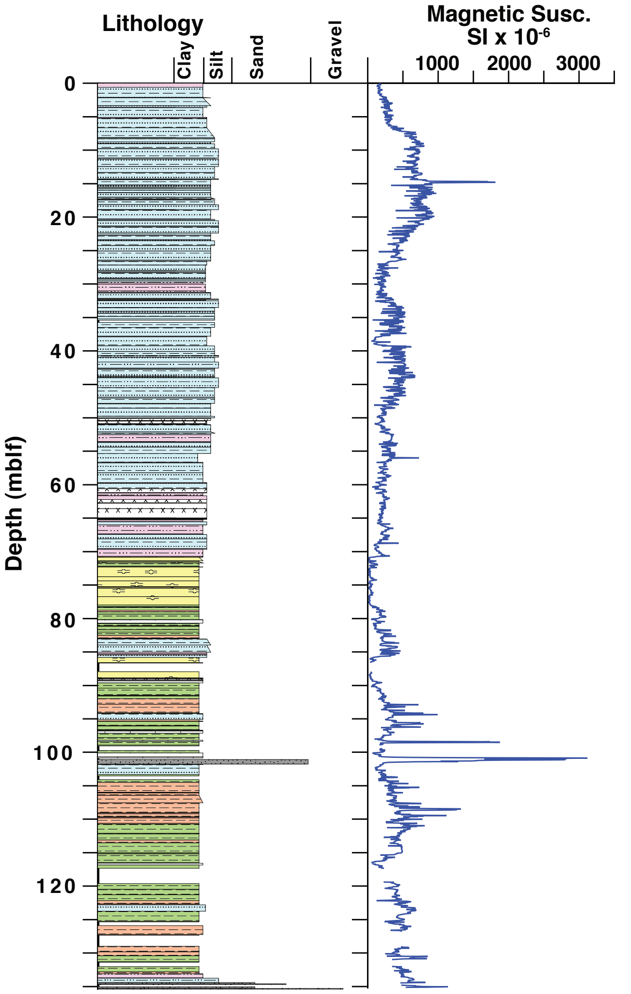

Figure 7. Summary stratigraphy of core TDP-TOW15-2A, based on initial core descriptions, and magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL. The key to the lithologic symbols is given in Fig. 6.

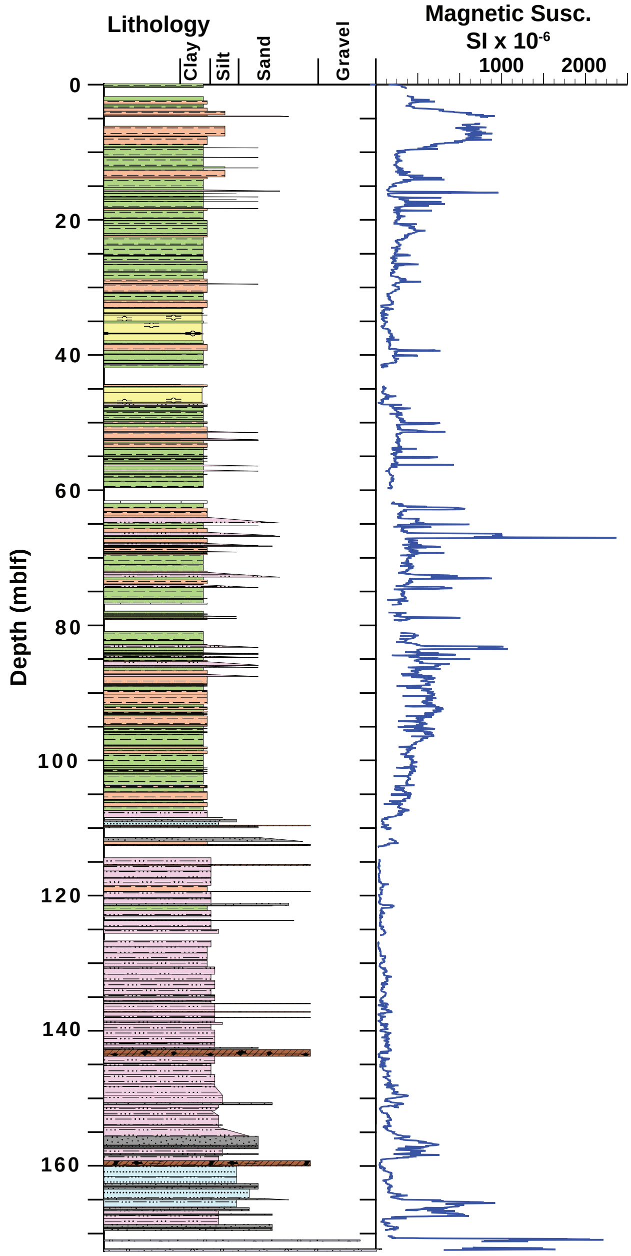

Figure 8. Summary stratigraphy of core TDP-TOW15-3A based on initial core descriptions, and magnetic susceptibility data measured on the whole (unsplit) core from the Geotek MSCL. The key to the lithologic symbols is given in Fig. 6.

slowly subsiding swampy plain. The rapid transition from Unit 2, which represents sedimentation near base level, to Unit 1, which represents sedimentation permanently below base level, suggests rapid fault movement and creation of accommodation space.

We interpret Unit 1 to represent sedimentation in a generally deep lake, with red/green alternations reflecting climate-driven transitions in lake level and mixing (Costa et al., 2015). Unit 1 sediments are quite similar at Sites 1 and 3, but differ substantially at Site 2, where the upper ~ 70 m of sediment predominantly consists of distal deltaic sedimentation. This supports our interpretation of the seismic reflection data and could indicate relatively recent establishment of the Mahalona River.

Magnetic susceptibility profiles from Lake Towuti show very similar patterns at all three sites, and show generally excellent correlation to borehole profiles (Fig. 9). These data, together with tephras, biogenic opal beds, and other distinct beds, allow for a preliminary correlation of cores from the three holes. This correlation highlights the relatively rapid influx of sediment to the upper 70 m of Site 2 relative to Sites 1 and 3, likely reflecting the rapid influx of sediment from the Mahalona River to the core site during this time. Interestingly, the basal sediments of Site 2 appear to be younger than those at Sites 1 and 3, despite the fact that Site 2 currently lies

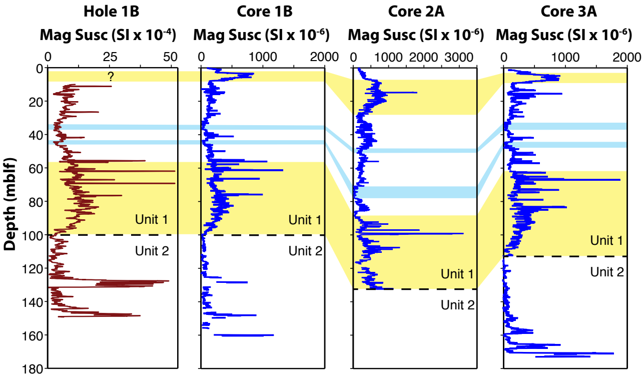

Figure 9. Magnetic susceptibility data from borehole logging of Hole 1B as well as MS data of cores 1B, 2A, and 3A. Yellow shading indicates correlative high magnetic susceptibility features in each site, whereas blue shading indicates correlative low susceptibility features. The dashed line marks the interpreted boundary between Seismic Unit 1 and 2; note that this boundary appears younger in core 2A than at sites 1 and 3.

in deeper water than the other sites. This could suggest relatively fast subsidence of the northernmost part of the lake relative to the central part of the basin, perhaps reflecting recent changes in fault motion.

Our analysis of these cores is just beginning and includes an array of geochronological, sedimentological, geochemical, geophysical, and biological methods. The geochronology is being assembled through a combination of $^{40}Ar/^{39}Ar$ ages on tephras, paleomagnetic, luminescence, and ^{14}C dating. State of the art isotopic, organic geochemical, and elemental methods are being applied to understand the climate history of the tropical western Pacific and the evolving biogeochemistry of the basin. Analyses of the pore fluid chemistry, Fe-mineralogy, and microbial communities in the sediments will reveal the nature of the deep biosphere that inhabits these iron-rich sediments, and fossil pollen and fossil diatoms will reveal the dynamics of the evolving terrestrial and aquatic biota in central Sulawesi. Ultimately, through interactions between these groups we will try to unravel the coupled tectonic, biologic, and climatic evolution of this unique system.

7 Data availability

Cores and project data are archived at the National Lacustrine Core Repository, USA and are under a 2-year moratorium during which time only project scientists have access. The data will become publicly available in 2018, but could, through request to LacCore, be made available earlier to other individuals on a case-by-case basis.

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Progress Reports

New drilling of the early Aptian OAE1a: the Cau core (Prebetic Zone, south-eastern Spain)

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Abstract. The Cretaceous was punctuated by several episodes of accelerated global change, defined as Oceanic Anoxic Events (OAEs), that reflect abrupt changes in global carbon cycling. The Aptian Oceanic Anoxic Event (OAE1a; 120 Ma) represents an excellent example, recorded in all major ocean basins, and associated with massive burial of organic matter in marine sediments. The OAE1a is concomitant with the "nannoconid crisis", which is characterized by a major biotic turnover, and a widespread demise of carbonate platforms. Many studies have been published over the last decades on OAE1a's from different sections in the world, and provide a detailed C-isotope stratigraphy for the event. Nevertheless, new high-resolution studies across the event are essential to shed light on the precise timing and rates of the multiple environmental and biotic changes that occurred during this critical period of Earth history.

Here we present a new drill core recovering an Aptian section spanning the OAE1a in southern Spain. The so-called Cau section was drilled in the last quarter of 2015. The Cau section is located in the easternmost part of the Prebetic Zone (Betic Cordillera), which represents platform deposits of the southern Iberian palaeomargin. The lower Aptian deposits of the Cau section belong to a hemipelagic unit (Almadich Formation), deposited in a highly subsident sector of the distal parts of the Prebetic Platform. Previous work on the early Aptian of the Cau succession has focused on stratigraphy, bioevents, C-isotope stratigraphy, and organic and elemental geochemistry. A more recent study based on biomarkers has presented a detailed record of the pCO_2 evolution across the OAE1a (Naafs et al., 2016). All these studies reveal that the Cau section represents an excellent site to further investigate the OAE1a, based on its unusually high sedimentation rate and stratigraphic continuity, the quality and preservation of fossils, and the well-expressed geochemical signatures.

1 Introduction

The occurrence of time intervals of enhanced deposition of organic matter (OM) during the Cretaceous, defined as Oceanic Anoxic Events (OAEs), reflect abrupt changes in global carbon cycling (i.e. Erba, 1994; Beerling and Royer, 2002; Dumitrescu et al., 2006; Jenkyns, 2010). The Aptian Oceanic Anoxic Event (OAE1a; about 120 Ma), represents one of the best examples of these events, with a global distribution recorded in all major ocean basins, and is associated with massive burial of organic matter in marine sediments. The OAE1a is concomitant with the "nannoconid crisis", which represents an episode of major biotic turnover (Erba, 1994; Erba et al., 2010), and is coincident with a widespread demise of carbonate platforms (Föllmi, 2012). The event has

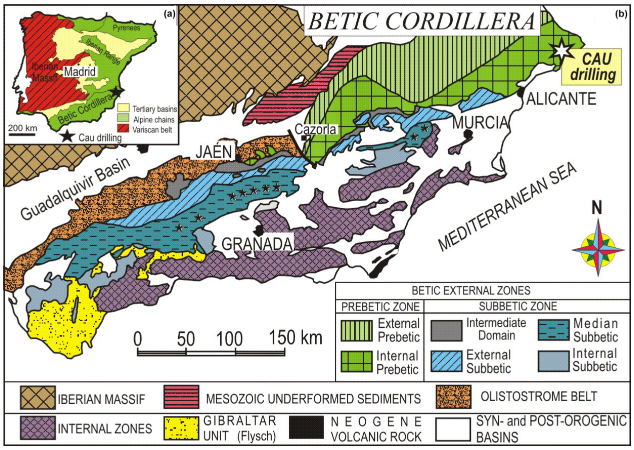

Figure 1. Location of the Cau section in the northern part of the Betic Cordillera in SE Spain. **(a)** National. **(b)** Regional geological setting.

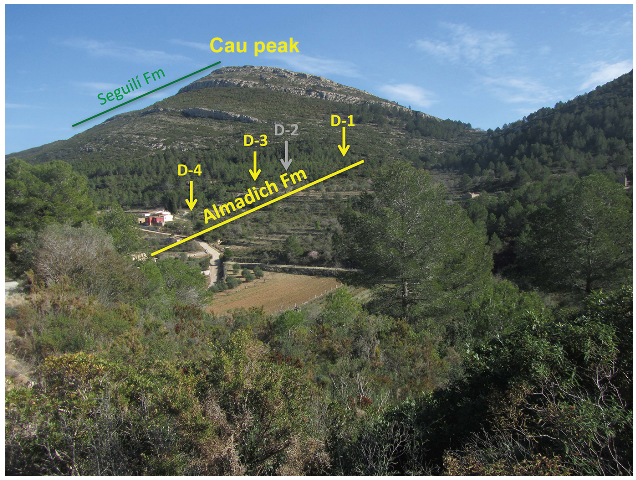

Figure 2. Panoramic view of the Cau section showing the position of the Almadich and Seguilí formations and the three drilling sites, D-1, D-3, and D-4, realized in 2015. Planned drill D-2 (in grey) was considered to be unnecessary and has not been performed.

been linked to a marked increase in sea-surface temperatures and $p\mathrm{CO_2}$, resulting in major changes in marine and terrestrial environments and biotas (Erba et al., 2015; Naafs et al., 2016). Much research has been done on the OAE1a from different sections across the world over the last decades (Schlanger and Jenkyns, 1976; Jenkyns, 1980; Arthur et al., 1985, 1990). A classic reference defining of the C-isotope stratigraphy of the event by Menegatti et al. (1998), has been widely applied by subsequent studies (see compilation in Erba et al., 2015). Among the most relevant questions are the origin of the carbon cycle perturbation, its potential association with submarine volcanic outgassing from the Ontong Java and other submarine plateaus, and the role of methane release from gas hydrates (Larson and Erba, 1999; Tejada et al., 2009). Although much multi-disciplinary research has been done on different OAE1a sections, additional high-resolution studies across the entire event will be crucial to shed light on the precise timing and rates of change of the different environmental and biotic perturbations that occurred.

In order to perform high-resolution studies, drill cores generally represent the best option. Previous coring of the OAE1a, with successful scientific results has been performed in two reference sections: the Cismon Apticore in northeastern (NE) Italy (Erba et al., 1999), and more recently, at La Bédoule in south-eastern (SE) France (Flögel et al., 2010; Lorenzen et al., 2013).

2 The Cau section

The Cau section is located in the NE portion of Alicante province (Fig. 1) and records deposits of the distal parts of a shallow carbonate ramp. In this setting, hemipelagic sedimentation took place during the late Barremian to late Aptian, before a progradational episode led to the deposition of shallow platform carbonates during the latest Aptian–Albian. The upper Barremian to upper Aptian is represented by the Almadich Formation (Fig. 2), made up by hemipelagic marls and marlstones with ammonites, planktonic foraminifers, and calcareous nannofossils. The shallow platform carbonates (above) are represented by the Seguilí Formation (Fig. 2). Figure 3 shows the lithostratigraphy, biozones, and bioevents of the Almadich Formation in the Cau section, along with bulk carbonate and total organic matter stable carbon isotopes (de Gea et al., 2003; Quijano et al., 2012; Naafs et al., 2016). A thick horizon of black marls corresponding to the OAE1a occurs in the lower part of the *Leupoldina cabri* planktonic foraminifer biozone, the *Hayesites irregularis* nannofossil biozone. The nannoconid crisis (Fig. 3) has been also recognized in this section (Aguado et al., 1999; de Gea et al., 2003). The stratigraphy, biostratigraphy, and isotope chemostratigraphy of the Cau section have been presented in detail in previous publications from outcrop studies made at a decimetre to metre scale (Aguado et al., 1999; de Gea et al., 2003; Castro et al., 2008; Naafs et al., 2016).

3 The Cau drilling

The OAE1a is represented in the Cau section by about 40 m of black and dark grey marls and marlstones. The expanded nature of the section along with its well-preserved palaeontological and geochemical records constitute the basis for its selection as the best OAE1a section in the Betic Cordillera, and thus provides one of the best known OAE1a records worldwide. The Cau drilling has been undertaken to allow very detailed sampling of the cores, in order to further increase the resolution attained from the outcrops. The authors

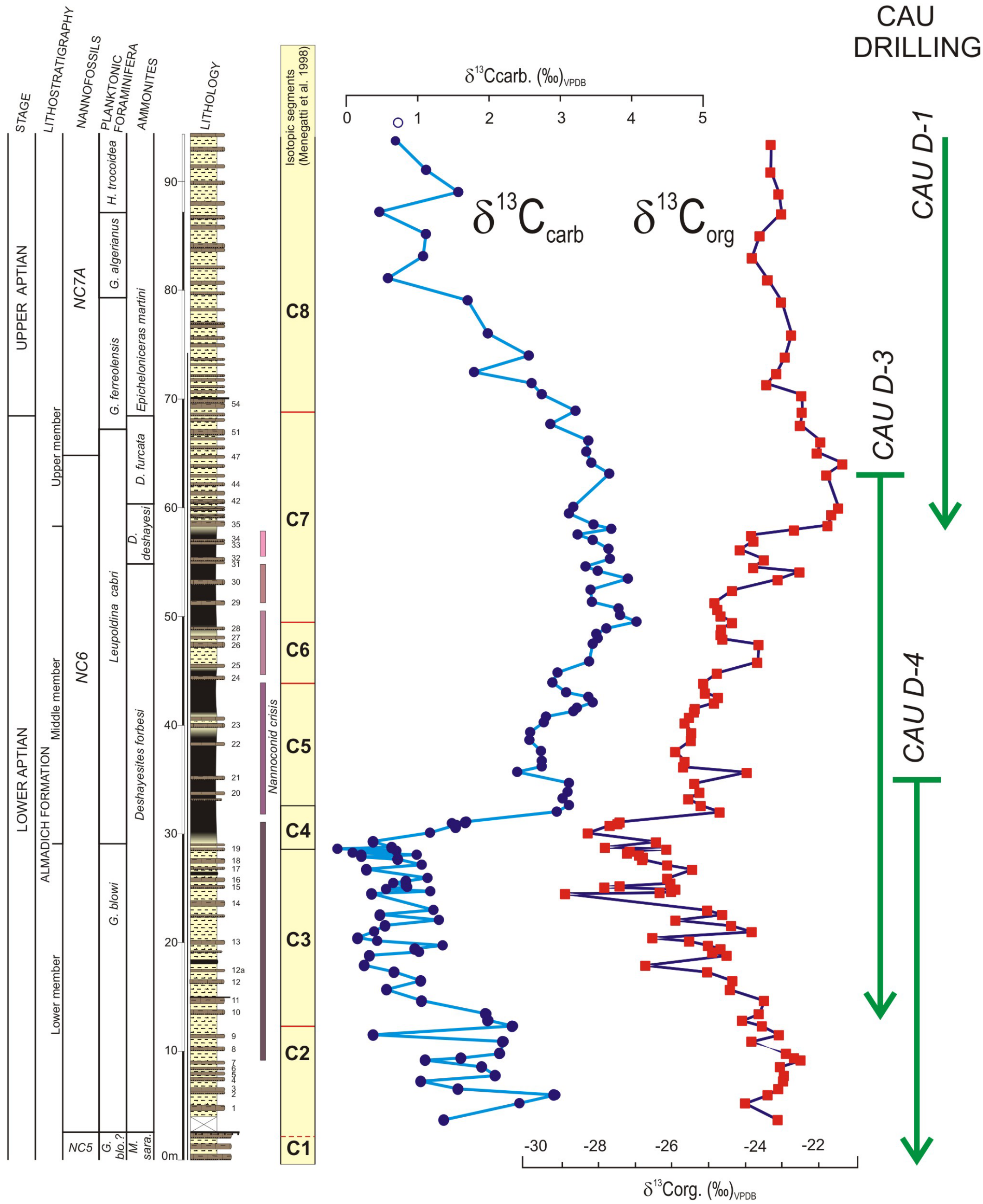

Figure 3. Stratigraphy of the Cau section: lithostratigraphy, biozones, and bioevents together with bulk carbonate (dark blue circles) and total organic matter stable carbon isotopes (red squares) (modified from Naafs et al., 2016). Isotope segments according to Menegatti et al. (1998). The parts of the succession recovered by each of the three drillings are shown to the right.

of this contribution form part of a new multidisciplinary research project focused on the study of the early Aptian in the Betic Cordillera. The project has been financed by the Spanish government.

According to the orientation of the strata in the Cau area, three drillings were carried out, located as shown in Fig. 2. The respective drilling depth reached: D-1 (56 m), D-3 (59 m) and D-4 (39 m). D-2 has not been drilled yet; we wait to confirm in the laboratory the overlap between D-1 and D-3. A total of 154 m of core have been obtained from the 90 m thick Almadich Formation, with a recovery of almost 100 %. The parts of the Cau succession cut by the D-1 to D-4 drillings are shown schematically in Fig. 3.

Outcrop biostratigraphic data from calcareous nannofossils, ammonites and planktonic foraminifera (Aguado et al., 1999; de Gea et al., 2003; de Gea, 2004) indicate that the

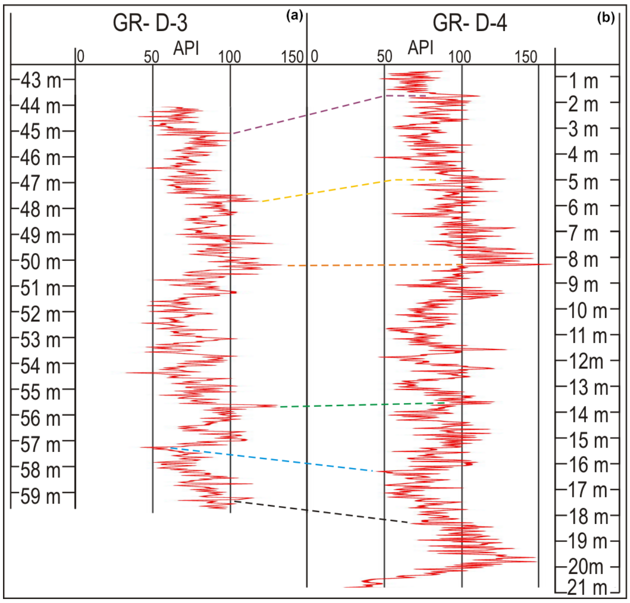

Figure 4. Correlation of gamma-ray logs from the **(a)** D-3 (metre 44 downwards) and and **(b)** D-4 (metre 1–21) drillings.

Figure 5. Massive and laminated, lightly bioturbated, facies of D-3 core between 14.15 and 15.20 m depth, and bioturbated facies of D-3 core between 54.07 and 55.71 m.

D-1 drilling cuts through upper Aptian sedimentary rocks that correspond to the NC7A calcareous nannofossil zone (Fig. 3). The D-3 and D-4 drillings cut through lower Aptian marly limestones and marls, the top of D-3 being placed in the upper part of *L. cabri* zone of planktonic foraminifera (uppermost part of the lower Aptian), while the D-4 cuts sedimentary rocks attributed to the lowermost part of the *L. cabri* and *Globigerinelloides blowi* zones. The deepest part of D-4 is late Barremian (NC5 zone) in age.

Initial correlation of the three cores is based on direct core observation and geophysical log profiles of the boreholes, including the gamma-ray log shown in Fig. 4. This figure shows the correlation of drillings D-3 and D-4, from metre 44 of D-3 downcore. In that way we have got a double core sampling of most of the record of OAE1a sediments (Fig. 4).

Figure 5 shows some examples of sliced cores with different lithofacies types, from massive and laminated to deeply bioturbated facies. The colour is dark grey, except for the heavily bioturbated intervals where a lighter grey colour is apparent.

4 Objectives

The drilling of the Cau succession aims to provide material to further document the record of OAE1a, and to advance knowledge of the environmental and biotic changes that occurred during this global event. The first objective is to undertake detailed description and sampling of the cores, in order to obtain sedimentological information. The C- and O-isotope stratigraphy will be obtained at a more detailed resolution than is currently available. This will serve as a basis to refine the correlation between the three cores and, most importantly, will provide a reference to analyse the perturbation of the global carbon cycle that occurred across the OAE1a. It will also enable comparison and correlation with other published records from sections worldwide, including those at Cismon (Menegatti et al., 1998; Erba et al., 1999), La Bédoule (Lorenzen et al., 2013), in the Basque Basin (Najarro et al., 2011; Millán et al., 2011), in the Pacific (Dumitrescu et al., 2006), and from the Boreal realm (Mutterlose et al., 2014).

In order to establish a more accurate age model than presently available, which is based on integrated biostratigraphy (Aguado et al., 1999; de Gea et al., 2003; Moreno-Bedmar et al., 2012), a cyclostratigraphy study is planned that will use the geophysical and geochemical time series. A quantitative nannofossil study will help to constrain the biostratigraphy, and will also analyse the environmental and biotic changes recorded by this fossil group, especially the nannoconid crisis. Additionally, we will address the relative roles of productivity and anoxia in the deposition of organic matter, which will be approached using a combination of geochemical (elemental and organic) and biotic (calcareous nannofossils, planktonic foraminifera, dinoflagellate cysts, among others) studies. Other environmental proxies to be considered are those related to pCO_2 and palaeotemperature reconstructions, volcanic activity and environmental changes in marine and terrestrial environments, including trace element geochemistry, biomarkers and clay mineralogy. The development of a set of multiple proxies from the same section within an accurate age model at a high stratigraphic resolution, will be crucial in order to advance our knowledge of the major episode of accelerated global environmental change (Föllmi, 2012) that occurred during the early Aptian.

5 Data availability

Previous and supplementary information supporting this research is available in tables, graphics, figures, pictures and the appendices of the references cited as well as in the online version of them.

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Scientific Drilling
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Report on ICDP workshop CONOSC (COring the NOrth Sea Cenozoic)

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Abstract. ICDP workshop COring the NOrth Sea Cenozoic focused on the scientific objectives and the technical aspects of drilling and sampling. Some 55 participants attended the meeting, ranging from climate scientists, drilling engineers, and geophysicists to stratigraphers and public outreach experts. Discussion on the proposed research sharpened the main research lines and led to working groups and the necessary technical details to compile a full proposal that was submitted in January 2016.

1 CONOSC project aims

The COring the NOrth Sea Cenozoic (CONOSC) project aims for continuous coring of the Cenozoic sedimentary record of the southern North Sea Basin. The headlines of the planned research are summarized in two main questions.

- *What is the long-term interaction between sediment accumulation and climate change?*
- *How does geographical isolation impact ecosystems divergence?*

In order to achieve this one has to investigate source–sink interrelationships, carbon burial, and river development in relation to changing Cenozoic climate gradients and evolving alpine tectonics in a site where terrestrial and marine signals can be integrated and compared. Furthermore, a high-resolution geologically and climatologically based timescale calibration of north-western Europe is needed to analyse the Cenozoic extinction rates, speciation, and migration patterns. The southern North Sea Basin combines a continued setting at the hinge line of land and sea, and active subsidence through much of the Cenozoic to meet conditions for obtaining such an integrated record.

Secondary objectives of the drilling project include detailed and direct downhole geophysical monitoring of natural and human-induced seismicity.

Although the North Sea Basin (NSB) is extensively drilled for hydrocarbons, the Cenozoic part of the infill is generally not targeted and high-quality cores as well as a high-resolution stratigraphical framework for this era are lacking. Therefore, CONOSC aims to drill the Cenozoic sedimentary record at two onshore sites in the Netherlands that collectively span the larger part of the Cenozoic in a marginal marine geological setting. The Quaternary and Neogene record will be targeted in the Roer Valley Graben in the south of the country, while the Paleogene will be retrieved from well-developed sequences in the northern part of the Netherlands. It is intended to core the full Cenozoic sequence at both sites, respectively ca. 1800 and ca. 1000 m.

The ICDP workshop in Driebergen/Utrecht addressed four main topics. First and foremost the science questions and technical challenges, such as downhole seismic monitoring. What is the problem to be solved and how innovative are the scientific contributions? Secondly, the feasibility of the project: what is known about the drilling sites, technical operations, well-logging methods, core treatments, and sampling? Furthermore, attention was paid to scientific partnerships and cooperation with external partners like E&P operators, regional authorities, and partners active in geothermal energy and subsurface storage. Finally, ideas on outreach and education were discussed.

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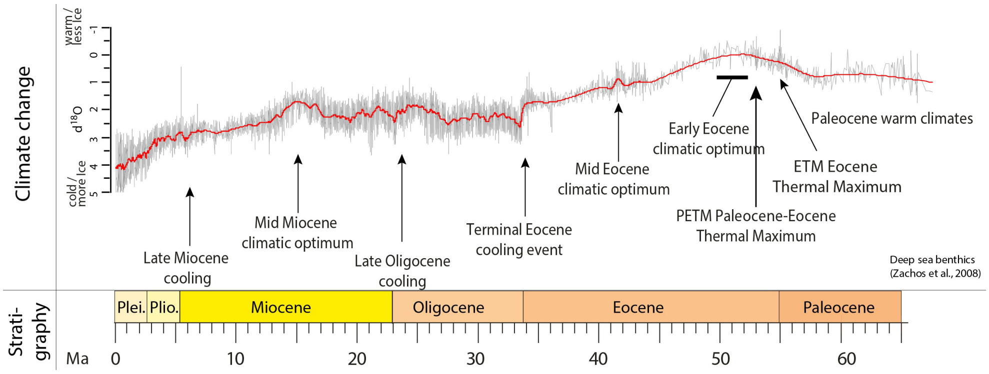

Figure 1. The main Cenozoic global climate events along the deep sea benthic isotope record (Zachos et al., 2008).

The CONOSC research plan is subdivided into six main themes, of which the discussion highlights are summarized in the following.

2 Palaeoclimatology and palaeobiology

One of the important issues in palaeoclimate and palaeobiology is that a high-resolution record of the Cenozoic in the NSB can be tied firmly into a regional and global context, and patterns can be quantified and compared. The cored Cenozoic sequences will provide detailed analysis of a number of globally significant events ranging from the early Eocene thermal maxima (PETM, ETM2, Fig. 1) to the conditions surrounding the arrival of hominins in north-western Europe and their impact on the NSB (Fig. 2). A key aspect is that the Cenozoic cooling seems much stronger here than in other parts of the world at similar latitudes, and that especially seasonality of the climate increased. Throughout the Cenozoic, the target regions experienced climates ranging from subtropical swamps to polar desert. Hence, the retrieved record can help to improve modelling warm temperatures at high latitudes (polar amplification), and specifically detect the varying role of the North Atlantic current in this region.

Both marine and terrestrial ecosystems experienced dramatic turnovers throughout the Cenozoic, but only partly due to climate. In north-western Europe in particular, increasing isolation though orogeny and seaway closure dramatically reduced the flora and faunal exchange and migration, leading to extinction and endemism. This may include the floristic response to increasing geographical (Alpine, Carpathian) isolation of northern Europe. But it will also show the effects on biogeography and evolution resulting from the closure of the Oligocene–Miocene interior seaways between the North Sea and the Mediterranean and the Paratethyan system. The rates and response times of these ecosystems transitions are key data that are currently lacking.

As the targeted sediments were deposited in a marginal shallow marine setting, they can contribute to understanding climate-induced changes of the terrestrial ecosystem with changing marine facies systems. Combined with a number of other proxies the pattern of changing (palaeo)climate can make a significant contribution to the understanding of the Cenozoic evolution of the NSB system. It also may contribute to understanding migration pathways of exotic species, especially during the lower Cenozoic in the NSB.

Other issues in this theme concern hydrological changes and sediment transport through river input during hyperthermals and subsequent cooling stages, to indicate signals for volcanism and tectonics, and the extent of euxinia in the NSB.

It is considered vital that a great number of biological and chemical proxies be analysed. Organic fossil groups are known to be very important in the basin (pollen and spores, dinoflagellate cysts), but also benthic and planktic foraminifera, and in selected intervals also nannofossils and molluscs. A number of geochemical techniques may be applied, e.g. stable isotopes, Rock Eval pyrolysis for the hydrogen and oxygen index (HI is a measure of the hydrogen richness in marine algae, lipids and proteins; OI measures the oxygen richness of a source rock due to high CO_2 and land plants, e.g. cellulose), which can be used in conjunction to estimate the origin of organic matter and thermal maturity of source rocks, TEX_{86}, and related lipid biomarker-based paleothermometers, combined with compound-specific $\delta^{13}C$, will be key to obtaining absolute climate reconstructions. Furthermore, it was suggested to incorporate outcrop studies available from the marginal areas of the NSB.

3 Stratigraphy and geochronology

A well-dated and detailed stratigraphical record of the marginal sedimentary record in the southern NSB is a prerequisite for establishing the palaeoclimate and palaeovegetational response from greenhouse to icehouse on the margins of this mid-latitude marine basin. Established timescales do provide a rough calibration, but the increasing isolation and changing biogeography and sediment provenance mean that many timescales are "floating" chronologies in north-western

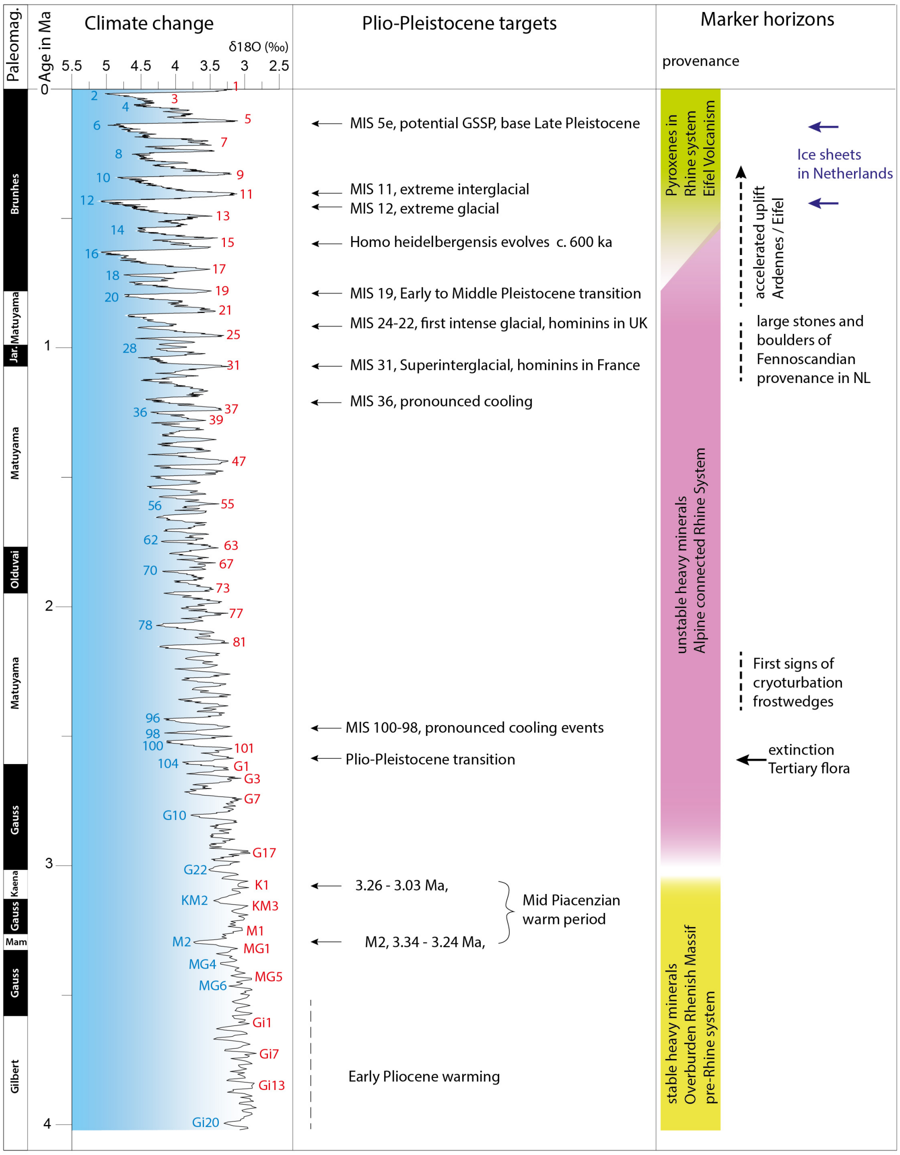

Figure 2. Late Pliocene–Pleistocene targets against the deep see benthic oxygen isotope stack of Lisiecki and Raymo (2005). The climate/vegetational context is very important for landscape reconstruction with respect to the northward migration of hominins.

Europe. Existing but outdated terrestrial standards can be much improved by providing the regional catchment-scale signals integrated with marine proxies. The improved biostratigraphy will allow a significant amount of earlier biostratigraphical work to be reappraised and integrated into a new synthesis for the regional Cenozoic basin evolution.

There are good opportunities to provide an integrated stratigraphy with dinoflagellate cysts as backbone, complemented with calcareous microfossils, potentially nannofossils, magnetostratigraphy, and selected calibration points from geochronology (e.g. OSL, $^{40}Ar/^{39}Ar$, U / Pb, $^{130}Th/U$). The integration of various approaches allows new dating methods to be tested (feldspar and quartz OSL). The development of a NSB cyclostratigraphy will be enhanced by downhole logging and imaging, high-resolution XRF core scanning, and analyses of other proxies (i.e. organic geochemistry, stable isotopes, magnetic susceptibility, tephra, and microtektites). Finally, a firm geochronology will give insights into the long-term climate-related changes in sediment supply.

4 Geohazards and monitoring

Current induced seismicity in the northern Netherlands urgently requires improved monitoring and fundamental knowledge of the exact origin to improve risk assessments

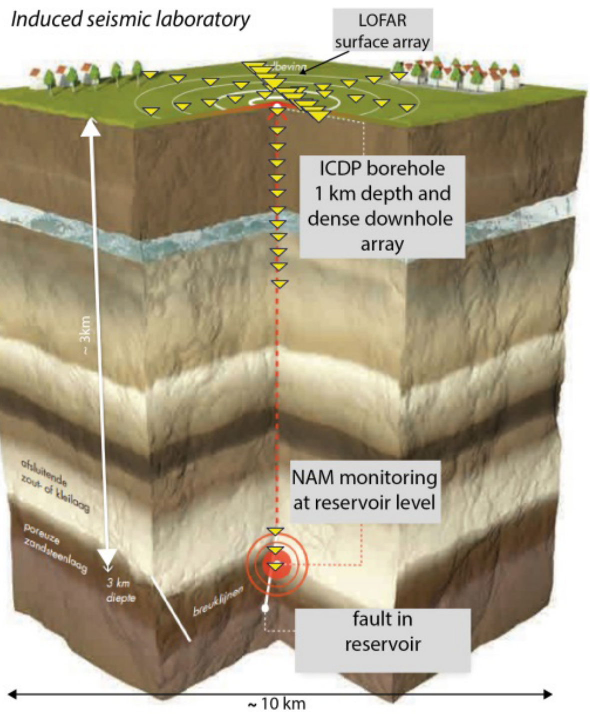

Figure 3. Schematic representation of a dense downhole array of seismic sensors coupled with a LOFAR surface array. Potential monitoring at the reservoir level falls outside the scope of CONOSC.

of mature gas fields in inhabited areas. The scientific drilling provides the opportunity to implement long-term seismic monitoring (more than 10 years) after coring, and possibilities for additional monitoring are being investigated (e.g. downhole temperatures, dynamics of freshwater to salt-groundwater transition, downhole pressures, and Earth magnetism). The seismic monitoring will be incorporated into the existing KNMI/NAM and LOFAR (low-frequency array) seismic 2-D networks (Fig. 3). The great depth (up to 1000 m) of installed sensors and the coupling to the LOFAR network will provide a 3-D component to the existing surface-based sensor networks. Due to the increasing number of human-induced earthquakes (resulting from gas extraction), there is high societal relevance for monitoring the northern site. The southern site is situated in the Roer Valley rift systems where naturally occurring earthquakes have been recorded since the Middle Ages. The largest known earthquake there had a magnitude of $M = 5.8$ in 1992 in the town of Roermond.

Scientifically long-term seismic monitoring is necessary for an in-depth understanding of induced earthquakes, fault reactivation, and rupturing. Data retrieved from greater depths are needed for validating existing geomechanical models. The dense downhole array will provide data that can be used to fill in the existing gap in regional-scale earthquake monitoring ($M \geq 1$) and reservoir-scale smaller seismicities ($M \sim -2/-3$). Furthermore, it is expected that earthquake detection and localization, especially below $M \sim -1$, will be improved considerably. Cooperation with NAM, operator of the large Groningen gas field, at the northern site may lead to a worldwide unique monitoring site in a producing gas field.

5 Physical properties and well logging

The scientific questions comprise such issues as sedimentation rates and cyclicities, which is a subject that is strongly related to a continuous and accurate geochronology. Palaeomagnetic logging is seen as a prerequisite for retrieving a highly accurate age model of the cored sequences. Careful core scanning can help to detect volcanic ash layers and even impact ejecta which may be very useful time markers. Core scanning and analysing provide detailed insights into a number of layer properties so far unknown for the Cenozoic sediments in the NSB. This includes amongst others the fundamental properties of clays (e.g. the Boom clay), quantification of heterogeneities and hydromechanical properties, etc. Gas (hydrocarbons and CO_2) in Cenozoic sediments forms an additional issue. Do we understand origin, timing, volumes, and gas-seepage systems that also have palaeoclimatic significance? In some cases high-quality, pressurized sampling is needed. The analysis of pore fluids also demands innovative approaches and careful sample treatment.

Combining geophysical subsurface monitoring methodologies and the downhole variations in properties is needed to improve the interpretative value of these methods. Time-lapse gravimetry can be applied to improve shear-wave and induced earthquake models.

6 Sedimentology and provenance

To determine the source and volumes of sediments deposited in the NSB, provenance studies have to be carried out. This can be done by combining different provenance indicators (e.g. XRF – bulk geochemistry; isotope analysis on zircons, micas, and feldspars; analyses of grain size and shape; pollen as source markers; clay mineralogy; and analysis of apatite fission-track provenance ages). A full data integration of these different proxies is seen as an innovative challenge: how to discriminate significant signals from general noise in the data sets and how to combine the provenance proxies with marine palaeobiological proxies? Complicating factors will be the reworking of sediment and lost or buried source areas. It is of great importance that existing archives of data (e.g. heavy mineral data at geological surveys and universities) can be explored and combined with newly retrieved data from the cores. Provenance data and a reliable age model will improve the insights into the evolution of drainage networks supplying sediment to the NSB. With respect to this aspect, the project will generate new palaeogeographical maps, and thus the (neo)tectonic and morphological evolution of the NSB will be known in greater detail than before.

7 Societal relevance and cooperation

Deep drilling up to 1000 m or more is often related to practical issues like mining, exploration, and exploitation of energy, water resources, and a number of governmental objectives. However, ICDP projects are primarily conducted to elucidate fundamental scientific questions and innovations.

Therefore, cooperation with industrial and scientific partners is of vital importance. In the course of developing a full proposal the CONOSC project has already involved a number of third parties that are interested in cooperating and contributing to the project. Some of them made specific demands on sampling; others will provide "in kind" contributions. It is intended to incorporate these activities as much as possible in the full proposal.

Equally important is the outreach to the general public and to explain why the scientific community conducts such a deep coring project in the NSB. Why do we want to know in great detail the past climate and evolution of the NSB, and why is Earth science a relevant science?

As the Netherlands is a densely populated country, public support and therefore outreach are of utmost importance. The CONOSC project has to generate early and open information channels to the broader public. Interest in CONOSC should be generated by linking the project to issues that are in the minds of people. Professional documentaries and videos showing the development of the project and the execution of the coring and sampling are seen as ways to help the project be embraced by the public. Recent IODP (https://www.iodp.org/multimedia) and ICDP expeditions (http://www.icdp-online.org/media/video-archive) have over the past years increased their outreach and education activities. Some recent videos were shared at the workshop, and it was decided that multimedia productions will be a key aspect of the communication surrounding CONOSC.

8 Final remarks

Numerous additional issues were discussed during the workshop that cannot be covered in this brief report. However, all information will used to compile the full proposal. Practical but crucial issues on sampling and coring will be elaborated in the next months. In order to get a quick initial idea on the ages and ranges of the cored sections, it is agreed that first a biostratigraphical analysis will be carried out on core catcher material. All discipline groups will use standardized analytical methods and we will also work on a generally applicable system for data management and evaluation. It is intended that the Geological Survey of the Netherlands will take care of core storage and sample treatment (i.e. core scanning, description, photographs, sub-sampling session). Together with ICDP they will look for the best solution in data management tools.

All participants, including potential partners to cooperate with, are thanked for their valuable contributions to the workshop and their open-minded attitude during the various discussions.

More information on CONOSC and its progress can be found on the project's websites (http://conosc.geo.uu.nl/; http://www.icdp-online.org/projects/world/europe/north-sea/).

Those interested in joining the CONOSC challenge are invited to contact Timme Donders (t.h.donders@uu.nl).

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Meet IODP and ICDP at IGC and AGU 2016

Joint IODP–ICDP exhibition booths will be organized at the 35th International Geological Conference (IGC) in Cape Town and the AGU Fall Meeting 2016 in San Francisco. The booths are focal points for the scientific drilling community to catch up with the latest news and achievements from both programmes. Scientists and visitors will also have the opportunity to meet the representatives of all programme partners and to get involved in both programmes.

IGC 2016, Cape Town, South Africa, 27 August–4 September 2016: booth #EE10

AGU 2016, San Francisco, USA, 13–18 December 2016: booths #312, 314 and 316

First Summer School in Petrophysics

The first Summer School in Petrophysics was held 26 June–1 July 2016 at the University of Leicester. This new course provided a unique opportunity to bring together experts from both academia and industry to deliver training in the theory and practice of petrophysics for 30 participants from the ECORD and IODP communities and beyond. Training focused on the application of downhole logging and core physical properties data to scientific questions, including lectures on geophysical principles, commonly used tools, case studies from both industry and IODP Science Plan themes, and project planning. Practical exercises, poster sessions, and a day of field visits focused on tool development and core interpretation served to provide a deeper understanding of the material.

Thirty early career scientists from 11 countries involved in scientific drilling attended the training course, which was sponsored by ECORD, UK-IODP, London Petrophysical Society, Aberdeen Formation Evaluation Society, and the Marine Studies Group of the Geological Society, with generous in-kind contributions from the U.S. Science Support Program, European Petrophysics Consortium, British Geological Survey, Schlumberger, and Weatherford.

Sally Morgan, UK-IODP Knowledge Exchange Fellow

USSSP Planning Workshops

The USSSP Workshop Program is designed to promote the development of new ideas to study Earth's processes and history using scientific ocean drilling. The programme encourages wide community involvement, including IODP and ICDP, to bring a broad, multidisciplinary approach to scientific questions and to explore new directions for research. Workshops may focus on a specific scientific theme or topic, or on a geographic region, integrating multiple topics. Regionally focused workshops offer opportunities to develop drilling proposals for future expeditions based on projected ship tracks, or to synthesize scientific results from past drilling projects.

Funding may be requested for small meetings or to support participants at larger international workshops. Broad-based scientific community involvement, co-sponsorship by related programmes, and the active participation of graduate students are strongly encouraged. Scientists who are interested in submitting planning proposals or taking part in upcoming workshops can find more information on the USSSP Workshops website (http://usoceandiscovery.org/workshops).

ICDP Conference on Operational Support

Supporting Continental Scientific Drilling:
A perspective from within and without

In 1996, the International Continental Scientific Drilling Program, ICDP, was founded to support scientific drilling; 20 years later, ICDP will be celebrating this 20th anniversary by discussing the way forward in drilling-related geosciences, how national funding agencies can strengthen continental scientific drilling in the future, and how ICDP's scientific technical support will be furthered and involved in upcoming projects. ICDP's Operational Support Group (OSG) has been an important element of ICDP since the beginning of the programme. It provides tools, instruments, and training as well as engineering and measurements for ICDP projects.

About 100 scientists and science managers will partake and contribute to this event. Major goals of the workshop-style meeting will be to intensify the role of the OSG and identify next-generation strategies in the fields of (1) samples – data – publication, (2) project management & engineering, (3) on-site measurements, and (4) outreach & training.

The meeting will take place on 20 to 21 October 2016 at the GFZ – German Research Centre for Geosciences in Potsdam, Germany.

Spain is back in ICDP

ICDP is pleased to announce the membership renewal of Spain in the ICDP. After resumption of the IODP ECORD membership earlier this year, Spain is now a full member of both programmes.

Schedules

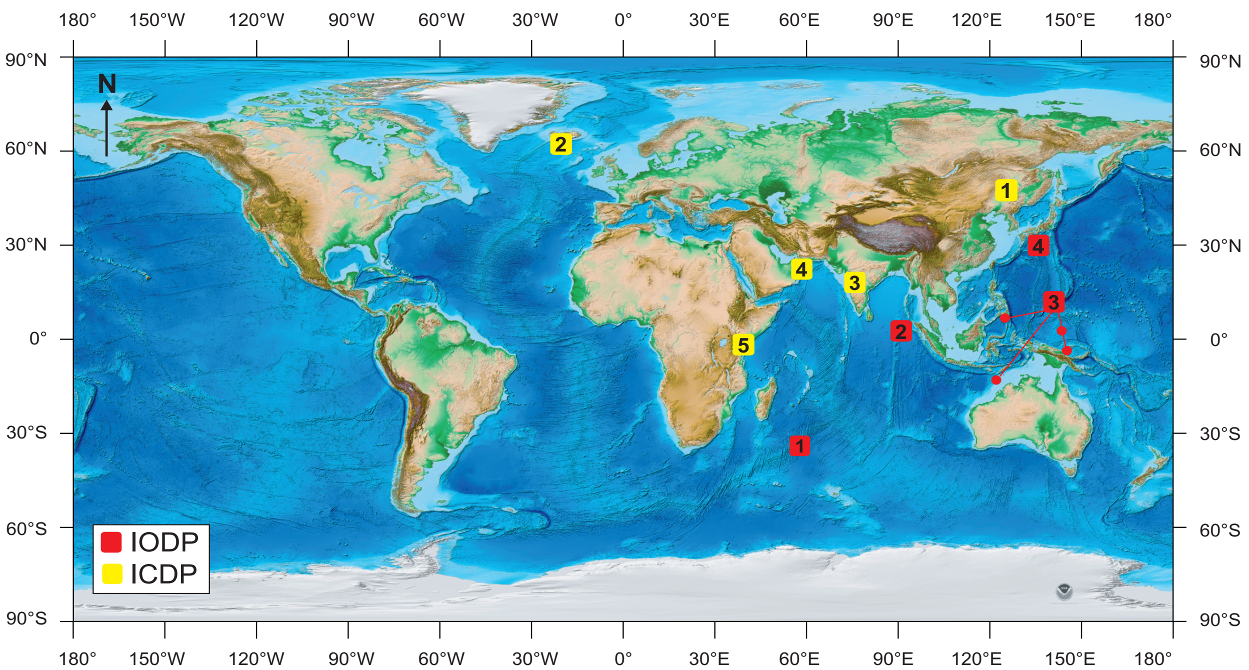
IODP – Expedition schedule http://www.iodp.org/expeditions/

USIO operations	Platform	Dates	Port of origin
1 362T Remediation U1473	JOIDES Resolution	4 Jul–6 Aug 2016	Cape Town / Colombo
2 362 Sumatra Seismogenic Zone	JOIDES Resolution	6 Aug–6 Oct 2016	Colombo / Singapore
3 363 Western Pacific Warm Pool	JOIDES Resolution	6 Oct–8 Dec 2016	Singapore / Guam
CDEX operations	**Platform**	**Dates**	**Port of origin**
4 370 Temperature Limit of the Deep Biosphere off Muroto	Chikyu	10 Sep–10 Nov 2016	Shimizu / Kochi

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

ICDP project	Drilling dates	Location
1 Songliao Basin	Apr 2014–Jul 2017	Songliao Basin, China
2 IDDP-2	Aug–Dec 2016	Reykjanes Peninsula, Iceland
3 Koyna	Oct 2016–Mar 2017	Koyna, India
4 Oman	Nov–Dec 2016	Oman
5 Lake Challa	Nov–Dec 2016	Kenya

Locations



Topographic/bathymetric world map courtesy of 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).