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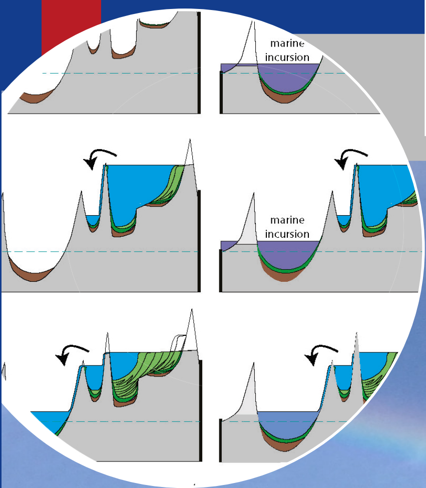
Reports on Deep Earth Sampling and Monitoring



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Editorial preface

Dear Reader,

This volume of SCIENTIFIC DRILLING focuses on better understanding of causal mechanisms of past rapid global climate changes and on extreme environmental disturbances. These are key problems in paleoclimate and paleoenvironmental research, critical for evaluating impacts of ongoing and future trends of our Earth's environment.
The role of the tropics in initiating, propagating, and responding to global changes requires information regarding the geographic distribution and timing of abrupt changes, including records that help to characterize fluctuations of the Intertropical Convergence Zone. The ICDP-supported MexiDrill coring campaign near Mexico City obtained records of past temperature and precipitation/evaporation variability and the response of terrestrial vegetation as well as aquatic flora and fauna (**p. 1**).
The Toarcian Oceanic Anoxic Event (T-OAE) interval was cored at Colle di Sogno and Gajum in the Lombardy Basin (northern Italy), the oldest Mesozoic case of global anoxia with widespread deposition of organic matter-rich sediments. These drill cores provide a complete and relatively expanded pelagic record from the western Tethys Ocean. Detailed multidisciplinary investigations are in progress to collect multi-proxy records for building a high-resolution dataset for modelling the nature and significance of the T-OAE (**p. 17**).
The Bouse Formation, a Neogene archive of the evolving Colorado River, is subject of an intense, controversial debate. Based on conflicting evidence from fossils, isotope geochemistry, and sedimentology, the Bouse Formation has either formed in marine or lacustrine conditions, or in some hybrid scenarios evolving over time. A workshop debated whether, where, and how a drilling and coring campaign could address (and perhaps resolve) the fundamental controversies surrounding the origin of the Bouse Formation, and how high-resolution drill-core records will enhance our understanding of the regional paleoclimate and paleohydrology evolution (**p. 59**).
The impact of submarine volcanism on environmental evolution has been discussed in three workshops with focus on future oceanic and amphibious research drilling, including volcanic rift margins, hot spot volcanism and caldera-forming volcanic eruptions.
The Campi Flegrei caldera, located along the eastern Tyrrhenian coastline in southern Italy, is an ideal site to investigate the mechanisms of caldera formation and associated post-caldera dynamics and to analyse the still poorly understood interplay between hydrothermal and magmatic processes. A MagellanPlus workshop held in Naples, Italy, explored the potential of the Campi Flegrei caldera as a target for an amphibious drilling project (**p. 29**).
The northeastern Hawaiian North Arch region is one of three potential sites for IODP mantle drilling to better constrain architecture, formation, and modification of oceanic plates and plate tectonics as the key driver of geological processes on Earth. The scientific targets for 2 km deep-ocean drilling in the Hawaiian North Arch region have been discussed in a workshop (**p. 47**) in Kanazawa, Japan. Finally, the Northeast Atlantic breakup volcanism and its role as a potential driver for the Paleocene–Eocene thermal maximum and influence on ocean circulation in the earliest phase of the northeast Atlantic Ocean formation were debated during a workshop in Kiel, Germany (**p. 69**). The workshop paved the way to new ocean and continental drilling proposals that would constrain the timing and rates of volcanism, vertical movements of rifted margins, and evolving Atlantic–Arctic gateways.

Your Editors
Ulrich Harms, Thomas Wiersberg, Jan Behrmann, Tomoaki Morishita, and Will Sager

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.

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Cover figures: Peter J. Fawcett (University of New Mexico).
Insert 1: Cohen et al.: The Bouse Formation, a controversial Neogene archive of the evolving Colorado River: a scientific drilling workshop report (28 Feb–3 Mar 2019, Bluewater Resort, Parker, AZ, USA (this volume).
Insert 2: Erba et al.: Coring the sedimentary expression of the early Toarcian Oceanic Anoxic Event: new stratigraphic records from the Tethys Ocean (this volume).

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Scientific Drilling
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Science Reports

Scientific drilling of Lake Chalco, Basin of Mexico (MexiDrill)

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Abstract. The primary scientific objective of MexiDrill, the Basin of Mexico Drilling Program, is development of a continuous, high-resolution ∼ 400 kyr lacustrine record of tropical North American environmental change. The field location, in the densely populated, water-stressed Mexico City region gives this record particular societal relevance. A detailed paleoclimate reconstruction from central Mexico will enhance our understanding of long-term natural climate variability in the North American tropics and its relationship with changes at higher latitudes. The site lies at the northern margin of the Intertropical Convergence Zone (ITCZ), where modern precipitation amounts are influenced by sea surface temperatures in the Pacific and Atlantic basins. During the Last Glacial Maximum (LGM), more winter precipitation at the site is hypothesized to have been a consequence of a southward displacement of the mid-latitude westerlies. It thus represents a key spatial node for understanding large-scale hydrological variability of tropical and subtropical North America and is at an altitude (2240 m a.s.l.), typical of much of western North America. In addition, its sediments contain a rich record of pre-Holocene volcanic history; knowledge of the magnitude and frequency relationships of the area's explosive volcanic eruptions will improve capacity for risk assessment of future activity. Explosive eruption deposits will also be used to provide the backbone of a robust chronology necessary for full exploitation of the paleoclimate record. Here we report initial results from, and outreach activities of, the 2016 coring campaign.

> Much is being written about climate change and the impact of rising seas on waterfront populations. But coasts are not the only places affected. Mexico City – high in the mountains, in the center of the country – is a glaring example.

"Mexico City, Parched and Sinking, Faces a Water Crisis" by Michael Kimmelman, The New York Times, 17 February 2017.

1 Introduction

Understanding causal mechanisms of past rapid global climate change is a key problem in paleoclimate research, critical for evaluating impacts of ongoing and future trends. In particular, the role of the tropics in climate shifts remains poorly understood; the interplay of extratropical conditions, including interhemispheric temperature gradients, with tropical climate change remains an area of ongoing research (Chiang, 2009; Chiang and Friedman, 2012; Abram et al., 2016). To evaluate the role of low latitudes in initiating and propagating (or responding to) global changes, we need information regarding the geographic distribution and timing of abrupt changes in the tropics, including records that help characterize Intertropical Convergence Zone (ITCZ) variability. The MexiDrill program's objectives include obtaining records of temperature and precipitation/evaporation variability and the response of terrestrial vegetation as well as aquatic flora and fauna to these changes to examine climate and ecosystem evolution on millennial to Milankovitch timescales. The field location is adjacent to Mexico City, one of the world's greatest population centers, which is vulnerable to changing hydrological balance. It is dependent on groundwater withdrawal for municipal use – this has led to significant ongoing subsidence – while also suffering from surface flooding.

The Mexico City region is subject to a range of volcanic hazards (e.g., Arce et al., 2005, 2013; Siebe et al., 2006, 2017), so the long archive of volcanic eruptions gives this record particular societal relevance. Explosive eruption deposits will be used to provide the backbone of a robust chronology necessary for full exploitation of the Chalco paleoclimate record. Current knowledge of pre-Holocene volcanic activity in the region is poor, and the new chronological work will also allow determination of the relationships between magnitude and frequency of explosive volcanic eruptions, providing a framework for risk assessment of future activity. The length of the Chalco sediment record provides a unique archive of regional volcanism: current knowledge of explosive eruptions is limited by sparse subaerial exposures and is non-existent beyond the latest Pleistocene. The new record will enable us to assess frequency patterns across the spectrum of regional volcanic hazards by drawing on a much longer and higher-resolution record of past activity. It will also enable us to evaluate how the region's stratovolcanoes, including Toluca and Popocatepetl, developed through time, and will provide insights into how the nature and long-term frequency of mafic eruptions in the Chichinautzin volcanic field (cf. Arce et al., 2013) have developed through time.

The Chalco sediment record will enable us to examine climate change, especially in hydrologic balance, on multiple timescales, including the following.

i. *Glacial–interglacial variation in moisture balance*. Prior studies of regional lake records suggest an influence of westerlies at 19–17 ka, bringing winter precipitation and mitigating otherwise extremely dry conditions (Bradbury, 2000; Metcalfe et al., 2007; Correa-Metrio et al., 2012). Similarly, Vasquez-Selem and Heine (2011) noted glacial expansion at the Last Glacial Maximum (LGM), with an associated 6–7° temperature decrease. Vasquez-Selem and Heine (2011) suggest westerlies as the moisture source, which is consistent with findings of a reduced NAM during the LGM by Bhattacharya et al. (2017). We hypothesize that during glacial maxima the Laurentide Ice Sheet influenced westerlies and associated storm tracks to enhance moisture inputs to central Mexico, likely in combination with decreased evaporation associated with lower temperatures, analogous to LGM conditions.

ii. *Variation of moisture balance among glacial periods.* Preliminary diatom (e.g., presence of *Stephanodiscus niagarae*) and sedimentological evidence implies that during MIS 6, Lake Chalco was colder and fresher than during MIS 2, consistent with evidence that regional glaciation at MIS 6 was $> 50\,\%$ greater in areal extent than LGM glaciation (Vasquez-Selem and Heine, 2011). The new deep Chalco sediment cores will enable us to investigate whether earlier glacial periods (e.g., MIS 6, 8, and possibly 10) were wetter than the LGM and how much hydrologic variability there was between these different glacial periods.

iii. *Precessional response.* Precession-driven insolation in subtropical zones typically leads to greater precipitation at times of increased regional insolation. We hypothesize that Lake Chalco's response to precession was most pronounced during insolation maxima within warmer interglacials (e.g., MIS 5e vs. MIS 7c and e). We can also investigate whether insolation maxima during glacial periods were sufficient to draw the ITCZ further north, increasing precipitation in the Basin of Mexico (BoM).

iv. *Millennial-scale response.* The BoM is within a regional gradient in a millennial-scale climate, at times showing sensitivity to ITCZ migration (analogous to Lago Petén Itzá and the Cariaco Basin) and at other times responding to shifts in locations of westerlies (like the Santa Barbara Basin, Cave of the Bells, and Fort Stanton Cave). The MexiDrill core will provide opportunities to compare MIS 2–4 (hypothesized to be drier glacial periods) with MIS 6 and 8 (hypothesized to be wetter glacial periods) to examine the amplitude of millennial-scale events, how they are reflected in a range of proxies, and how millennial-scale variability is expressed at each of the terminations. We hypothesize that millennial-scale variability during glacial terminations was similar at Terminations I, II, and III, as suggested by the synthetic record of the Greenland climate (Barker et al., 2011).

v. *Volcanic history.* Volcaniclastic deposits in the Chalco core are likely to be dominated by tephra fall deposits, based on past research in the area (Ortega-Guerrero and Newton, 1998). Felsic deposits are likely to be derived predominantly from large explosive eruption deposits from the Nevado de Toluca and Popocatépetl stratovolcanoes, with several possible additional regional sources and mafic deposits from the monogenetic centers of the nearby Sierra Chichinautzin volcanic field. These tephra deposits can be used to explore the long-term development of these contrasting volcanic systems on 10^4–10^5-year timescales. By identifying sources of deposits throughout the core, we will establish whether systematic variation in eruption frequency or composition has characterized the growth of these volcanoes. Has activity in the Sierra Chichinautzin field been stable or episodic, and how does Holocene activity fit into this pattern? Is there cyclicity (or are there major shifts) in the pattern of explosive eruptions at Popocatépetl and Nevado de Toluca, and is this linked to currently recognized periods of edifice growth and destruction (cf. Siebe et al., 2017)?

1.1 Site description

The BoM (19°30′ N, 99°W; 9600 km^2, 2240 m a.s.l.) is a hydrologically closed basin in the TransMexican Volcanic Belt (TMVB, Figs. 1–2). The emergence of the southern Chichinautzin volcanic field since 1.0 Ma (Arce et al., 2013) has been linked to closure of the basin and development of a lake system. Continued subsidence of this intermontane basin accommodated the accumulation of hundreds of meters of lacustrine sediments (Ortiz Zamora and Ortega Guerrero, 2010). Lake Chalco, the location of the MexiDrill site, was the southernmost of these lakes; its proximity to the volcanic peaks that contain the headwaters of streams feeding the lakes has made it the freshest of the lakes and likely the location of the most continuous sedimentation. Mexico City (then called Tenochtitlan) was established by the Aztecs in the 1300s on an island in the center of Lago de Texcoco (to the north of Chalco). In more recent times, the hydraulic regime of the BoM was heavily modified, lowering the water table to improve flood control, accommodate agricultural expansion, and provide water for urban development. The plain of Lake Chalco, located in the southeasternmost sub-basin of the BoM (Fig. 1), has an area of 120 km^2 (Caballero and Ortega Guerrero, 1998), though the lake has been reduced to a shallow marshy remnant (Caballero Miranda, 1997).

An array of climate systems affects central and southern Mexico. Episodic northward surges of the ITCZ bring summer rains (Metcalfe et al., 2015). This circulation is distinct from that of the North American Monsoon (NAM). The BoM thus contrasts with northern Mexico and areas of the southwestern USA where the NAM delivers summer precipitation (greater than 60 % of the annual total) driven by land surface heating and convection on the high topography (Adams and Comrie, 1997). Modest winter season precipitation in central and southern Mexico is often associated with the southward penetration of mid-latitude frontal systems, locally known as “Nortes” (Reding, 1992; Pérez et al., 2014; Stahle et al., 2016).

Interannual variability of climate over Mexico is strongly influenced by ocean–atmosphere interactions, including the El Niño–Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and the Pacific Decadal Oscillation (PDO) (Magaña et al., 2003; Metcalfe et al., 2015; Stahle et al., 2016). Of all of these, ENSO has the strongest impact both in magnitude and stability of the teleconnection between sea surface temperatures and precipitation, but varies with both latitude and season. El Niño is associated with wet winters in the north but with drier summers over southern Mexico including the BoM (Magaña et al., 2003). The net result of these interactions is that modern precipitation in the BoM varies with northern Mexico and the southwestern USA on annual and interannual timescales, when ENSO and PDO have significant impacts. However, when a 20-year low-pass filter removes those influences, BoM precipitation is distinct from both regions (Fig. 2).

1.2 Prior work

The potential value of the Chalco Basin sediment archive has been recognized for decades (e.g., Sears and Clisby, 1952; Bradbury, 1989), and a number of previous studies demonstrated the sensitivity of the system to climate changes, particularly to regional hydrological balance. These studies primarily focused on the past 40 kyr, utilizing rock magnetism and pollen and diatom distributions to reconstruct paleoenvironmental conditions (Bradbury, 1989; Lozano García et al., 1993; Lozano García and Ortega Guerrero, 1994; Urrutia Fucugauchi et al., 1994, 1995; Lozano García and Xelhuantzi López, 1997; Caballero Miranda, 1997; Caballero and Ortega Guerrero, 1998). Broadly, these studies indicate that lake level was highest prior to 35 ka, shallowed from 30 to 22.5 ka, and deepened from 22.5 to 10 ka, with maximum post-LGM freshening between 14 and 10 ka. During the early Holocene, the lake became shallow and marshy (consistent

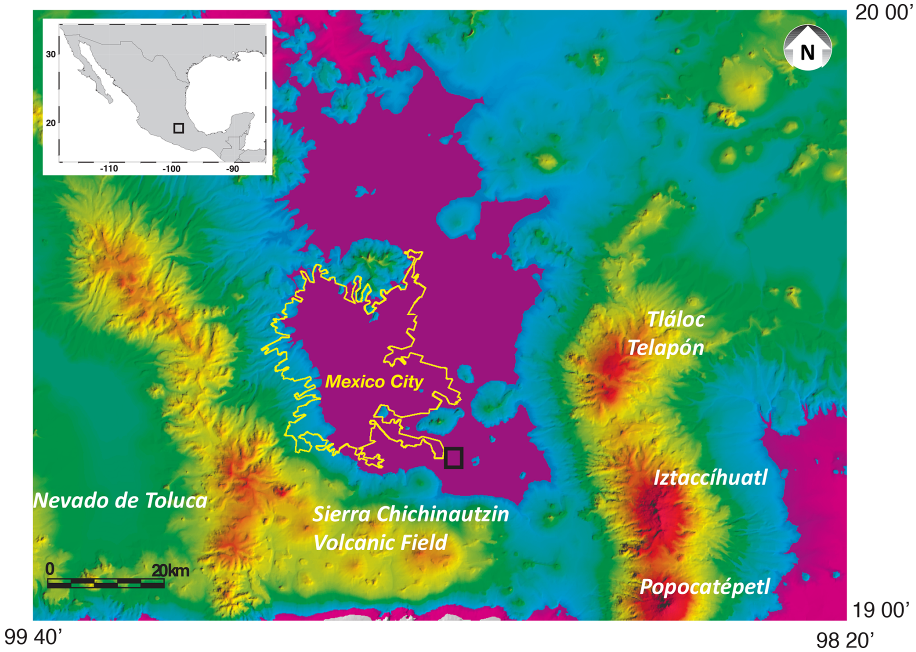

Figure 1. Site map of the Basin of Mexico, showing the extent of the paleolake (flat magenta areas), the developed areas of the megalopolis, and locations of coring sites in Chalco (black box).

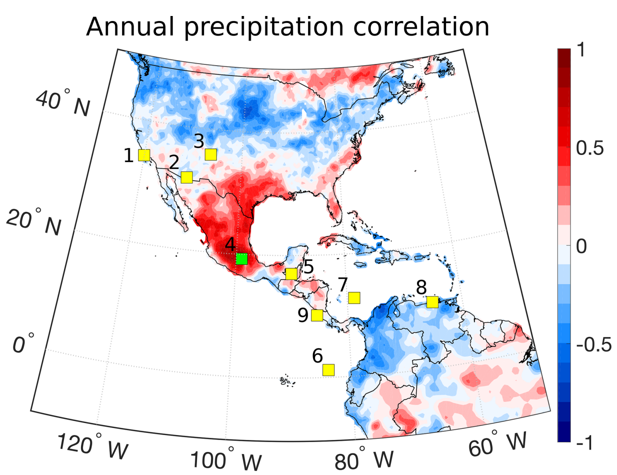

Figure 2. Locations of long paleoclimate records from the northern tropics and subtropics of the Americas and correlation among regional precipitation patterns. 1. Santa Barbara Basin (ODP site 893); 2. Cave of the Bells, AZ; 3. Valles Caldera, NM; 4. Lake Chalco, Mexico; 5. Lago Petén Itzá, Guatemala; 6. Panama Basin (ODP 677B); 7. Nicaragua Rise (ODP 999A); 8. Cariaco Basin (ODP site 1002); 9. Terciopelo Cave, Costa Rica. Red and blue shading depicts the correlation (r) between annual precipitation at Chalco and all the other locations (1901–2013 CE; 10-year low-pass filter; 0.5° spatial resolution). The precipitation data are the mean of three gridded products: University of Delaware v5.01 (Willmott and Matsuura, 2001); Global Precipitation Climatology Center V7 (Schneider et al., 2016); and University of East Anglia CRU TS v. 4.03 (Harris et al., 2014).

with the general drying trend of central Mexico; Metcalfe et al., 2000). More recently, Lozano-García et al. (2015) identified millennial-scale rainfall variability in the Chalco Basin during MIS 3, observing that regional runoff was lower during the LGM than during deglaciation, which contrasts with some other regional records such as Lago Petén Itzá (Hodell et al., 2008). Torres-Rodríguez et al. (2015) developed an 85 kyr record of drought and related fire history recorded in Chalco sediments showing increased fire frequency during MIS 3 in association with higher spring insolation. Finally, Correa-Metrio et al. (2013) demonstrate that Chalco and Petén Itzá both have similar post-LGM rapid warming histories and that the velocity of climate change at that time was one-fourth that of the last 50 years.

2 Site surveys

2.1 Deep borehole surveys

Earlier characterization of deep BoM sediments was motivated by a need to understand the basin's structure for evaluation of seismic hazards and of groundwater resource sustainability. After the 1985 Mexico City earthquake, five deep (∼ 2 km) boreholes were drilled to characterize sediments and underlying volcanic sequences in the BoM, and to evaluate the Cretaceous carbonate basement. Analyses of well cuttings showed that the uppermost section, a lacustrine sequence of volcanic ash and sand intercalated with clays, is present across the BoM with a variable thickness up to 300 m. These surveys also indicated the presence of a deeper lacustrine sequence, 100–200 m in thickness, composed of gravels, clayey sands, and marls as well as granular volcanic material below an intervening volcanic unit (composed of Pliocene and Quaternary tuffs, lavas, and conglomerates). This lower sequence forms the Chalco Aquifer (Krivochieva and Chouteau, 2003). The survey found the thickest sedimentary pile at the Tulyehualco-1 borehole, located at the western end of the Chalco Basin, leading subsequent researchers to target that locale for further study.

2.2 Geophysical surveys for drill site selection

Seismic reflection surveys are a commonly used approach for selecting a drill site location with a long undisturbed record of continuous deposition. In lacustrine or marine conditions, acquisition of suitable seismic reflection data is a relatively straightforward exercise. Depending upon the depth of the target, suitable images of the sedimentary section can be easily achieved using either single-channel or multi-channel marine seismic surveying techniques. Collecting multi-channel seismic reflection data on land is far more challenging. Unlike the marine environment where the source and receivers are deployed in a relatively homogenous medium (the water column), on land the near-surface material is typically heterogeneous, often significantly negatively impacting the propagation of seismic energy.

In the Chalco sub-basin, the near-surface conditions have been severely impacted by the intensive agricultural development of the area. This resulted in significant reworking and amendment of unconsolidated near-surface soils and sediment. As a consequence it is difficult for surface-deployed seismic sources to couple sufficient energy into the underlying sediments to collect any meaningful seismic reflection data. Under such conditions, collection of high-quality seismic reflection data would require that the source (and possibly the geophones) be buried below the disturbed near-surface. Alternatively, *Vibroseis* vibrator trucks could inject energy into the underlying basin to produce meaningful reflections. Collecting the survey using either of these approaches would not have been feasible, as they would have entailed a field cost comparable to that of the actual drilling program.

We undertook a seismic reflection survey in 2011, with a strategy of using a *Mini-Sosie* source composed of an array of earth compactors to generate a randomly swept signal that could be processed in a similar fashion to *Vibroseis* surveys. However, once this survey was initiated it became apparent that the source was not capable of generating sufficient energy to pass through the unconsolidated and disturbed upper sections of Chalco sediments and produce meaningful reflections. Ultimately, the survey was acquired using a *PEG-40* source, which generates seismic energy by striking a metal plate with an accelerated mass. The shot records produced by this source were significantly better than those generated by the *Mini-Sosie*, but still yielded few reflections and did not produce satisfactory survey results.

2.3 Other geophysical techniques

The inherent difficulty in utilizing standard seismic reflection techniques in this setting led us to employ a suite of non-traditional geophysical techniques to build a consistent picture of sediment thicknesses across the Chalco Basin. These techniques – subsidence mapping, gravity surveys, and passive seismic surveys – do not provide information on continuity of sedimentation or the presence of faults offsetting the sediments, but provided a consistent body of evidence that indicated a maximum sediment thickness of ∼ 300 m at the identified drilling location. In addition, transient electromagnetic (TEM) and magnetotelluric (MT) soundings undertaken at the time of the 2016 drilling campaign (Bücker et al., 2017) provide similar conclusions.

- *Subsidence mapping.* Since the 1950s several areas of Mexico City, including the Chalco sub-basin, have experienced notable surface subsidence resulting from groundwater withdrawal for municipal needs that has caused the water table to drop. Subsidence rates are broadly correlative with the thickness of lacustrine sediment sequences and may thus be used to evaluate relative depth to basement across the basin. Combined interferometric synthetic aperture radar (InSAR) and GPS data reveal that parts of Mexico City have experienced subsidence rates that exceed 350 mm yr^{-1} (Cabral Cano et al., 2008, 2010). In the Chalco sub-basin these rates exceed 200 mm yr^{-1} and indicate maximal sediment thickness near the center of the basin (Fig. 3).

- *Gravity surveys.* Bouguer gravity anomaly maps produced by Enrique Cabral Cano (personal communication, 2014) as part of a recent reinterpretation of 1950s vintage regional gravity data from the Valley of Mexico (Hernández-Moedano and Grauel, 1954) suggest that the study area is underlain by more than 300 m of sediment that fill an E–W trough. This has been interpreted as a graben bounded on the north by the Sierra Santa Catarina and Cerro de la Estrella and to the south by a horst-shaped block composed of the Teuhtli and Xitle volcanoes (Campos-Enriquez et al., 1997).

- *Passive seismic H/V spectral ratios.* In conjunction with our 2011 seismic reflection survey, we undertook a passive seismic H/V spectral ratio survey (Nogoshi and Igarashi, 1971; Nakamura, 1989) across the Chalco Basin. Three-component recordings of the ambient seismic wavefield were made at locations in the field area. The seismic response of the sediment pile illuminated by the seismic energy is not uniform; it resonates at specific frequencies that are tied to the seismic properties of the sediments and the thickness of the sediment pile.

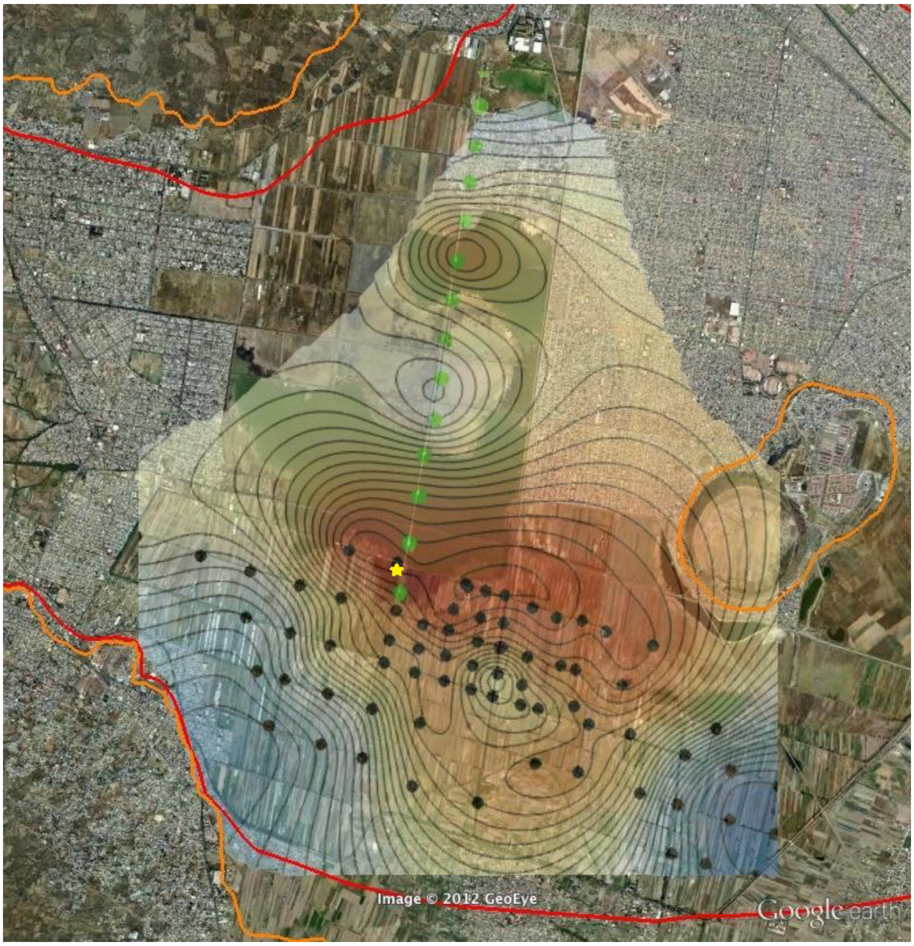

Figure 3. Thickness of the lacustrine sedimentary package below the Chalco sub-basin calculated from resonance frequencies determined from H/V spectral ratios. Red and orange lines represent contacts between the lacustrine and transitional geotechnical zones and between the transitional and the hillslope geotechnical zones, respectively (Gobierno del Distrito Federal, 2004). Water wells with known sediment thicknesses (Ortiz Zamora and Ortega Guerrero, 2010; green dots) were used as calibration points for individual passive seismic measurements (white dots). The color scale (blue–white–red) represents thicknesses of 0 (blue) to more than 300 (red) meters. The contour interval is 10 m. The selected drill site (yellow star) was where this survey indicated the thickest sediment pile, just to the south of the existing lake. © 2012 GeoEye and © Google Earth.

The ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components of the ambient noise vibrations recorded at a common location can be used to identify the resonance frequency of the sediment package below the observation point (SESAME, 2005). We developed a calibration function by recording resonance frequencies at a series of water wells where the depth to the base of the lacustrine sediment package was known. We then measured resonance at grid points across the basin to construct a map of sediment thickness (Fig. 3), which shows maximal thicknesses in the areas indicated by subsidence mapping and gravity anomalies.

3 Drilling, logging, and onsite operations

3.1 Drilling and onsite operations

During the 2016 ICDP Mexidrill drilling campaign, three long drill cores (1A, 1B, 1C; see Table 1) were retrieved in the Chalco Basin, recovering the entire lacustrine sequence (upper 300 m) and continuing into the volcanic basement, down to 522 m total depth (Fig. 7). A suitable drilling site was identified in the agricultural fields in the Tulyehualco district, near the depocenter of the lake basin. Drilling was performed by Major Drilling de Mexico S.A., using a truck-mounted Boart Longyear LF90 rig with standard Boart Longyear HQ3 wireline diamond coring tools (Fig. 4); 1.5 m long core sections of 61 mm diameter were collected in polycarbonate liners. HWT casing was advanced as needed to sta-

Figure 4. Field images mosaic. Panels **(a)** and **(b)** are southeastward views from the field area showing the prominent stratovolcanoes Iztaccihuatl and Popocatépetl, which are, respectively, to the left and the right in these images. Panel **(c)** is a west-southwest view from the drill site looking toward Teuhtli volcano, one of the cones within the Sierra Chichinautzin volcanic field. Panel **(d)** is a northeasterly view of the Chalco Basin with the drill rig.

bilize the formation during continued drilling, and later retrieved, and drill fluid returns were processed in a centrifuge to separate solids and allow recirculation. All drilling used municipal water delivered to the site, with a tracer added to allow post-drilling assessment of fluid contamination in the core samples (Friese et al., 2017). Drilling operations began on 23 February 2016 and concluded on 30 March 2016, in two daily shifts of 12 h each. To improve recovery in the uppermost soft sediments, an additional shallow fourth hole (1D) was cored by hand on 1–2 April 2016 with a Usinger-type percussion corer (Mingram et al., 2007), with cores extruded into secondary liners.

On retrieval, cores were extracted from the drilling tool, capped, sealed with tape, and labeled according to standard LacCore/CSDCO protocols. Drilling metadata were captured throughout operations and transferred to ICDP and to the LacCore Facility for integration with all project datasets. Cores were passed through a Geotek MSCL-S with a magnetic susceptibility loop sensor after drilling, for high-speed, low-resolution assessment of stratigraphic completeness. At the conclusion of drilling, cores were crated and shipped via air freight to the LacCore Facility at the University of Minnesota for processing, description, scanning, subsampling, and permanent curation in the LacCore repository in refrigerated conditions (4 °C).

3.2 Downhole logging

The Leibniz Institute for Applied Geophysics (LIAG) conducted geophysical downhole logging in the 1A borehole. Initially, the upper section (0–195 m) was logged, and after drilling of the second part down to 420 m, the logging was completed to total depth. The following tools (measurements) were run: spectral gamma ray (SGR: total gamma ray;

Table 1. Summary data for drilling sites and cores.

Borehole ID	Borehole IGSN	Latitude	Longitude	Elevation (m)	Total depth (m)	Cored length (m)	Recovery (m)	Recovery (%)
MEXI-CHA16-1A	CDR0004DR	19.25718	−98.97549	2227	423	423	373	88 %
MEXI-CHA16-1B	CDR0004DS	19.25718	−98.97554	2227	313	313	286	91 %
MEXI-CHA16-1C	CDR0004DT	19.25733	−98.97560	2227	522	425	392	92 %
MEXI-CHA16-1D	CDR0004DU	19.25707	−98.97541	2227	19	19	17	91 %
Total					1277	1180	1068	91 %

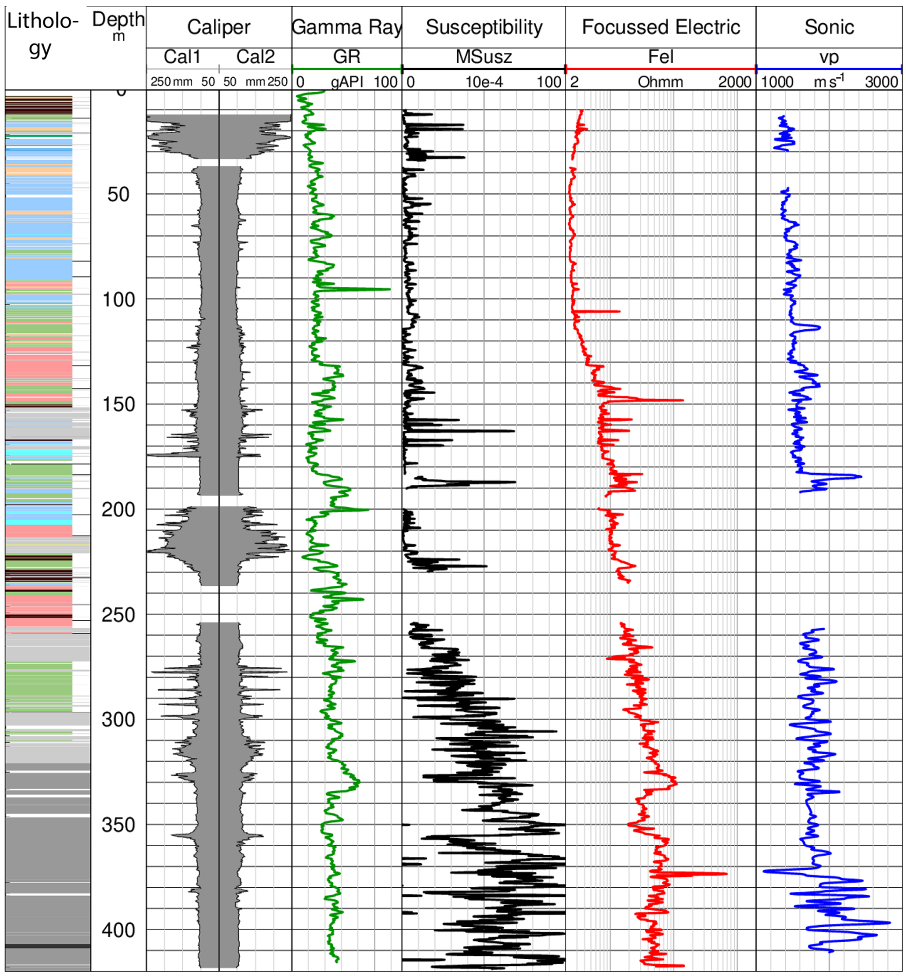

Figure 5. Downhole logging data of the 1A borehole: Cal1 and Cal2 – caliper (in millimeters); GR – gamma ray; MSusz – microsusceptibility; Fel – focussed electric resistivity; vp – compressional velocity; lithology from core. Lithology legend in Fig. 8.

potassium, uranium, thorium), magnetic susceptibility (Susz: susceptibility with standard and micro resolution), focused electric resistivity (Fel), dipmeter (caliper and resistivity), acoustic borehole televiewer (borehole image), sonic (velocity vp), as well as salinity and temperature. All the instruments – except the SGR – require an open hole. Therefore, after measuring the SGR through the pipe over the complete depth, the drill string was pulled successively to guarantee the stability of the borehole, and the remaining tools were run. The first data processing step is to splice the data to produce a continuous log over full depth. Figure 5 shows some of the geophysical properties over the complete length (0–420 m) of the 1A borehole. Gaps within the logs were caused mostly by challenging borehole conditions. Gamma ray data show quasi-cyclic variations in different period ranges, possibly representing glacial–interglacial to sub-orbital climate

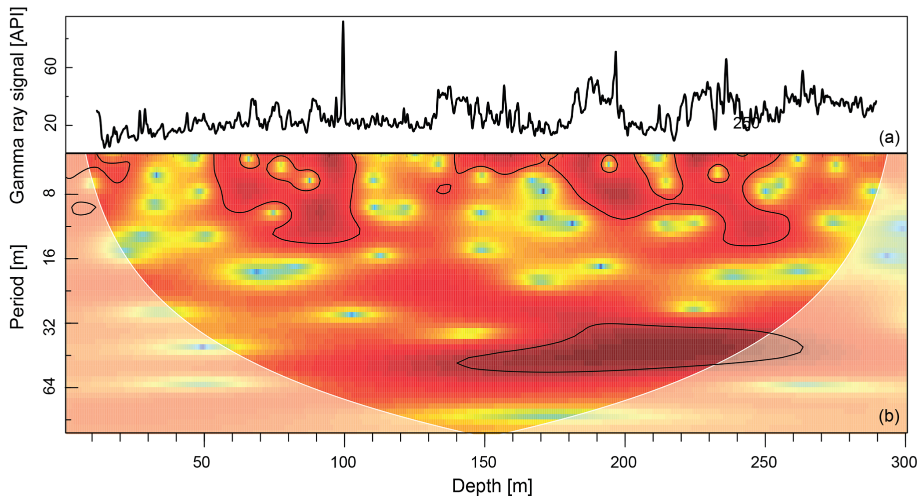

Figure 6. Wavelet analysis (Gouhier et al., 2018; **b**) of (total) gamma ray data **(a)** from the upper 300 m of Lake Chalco sediments. Red colors indicate strong cyclic behavior and black markings indicate the results of a significance test. White coloring indicates the cone of influence.

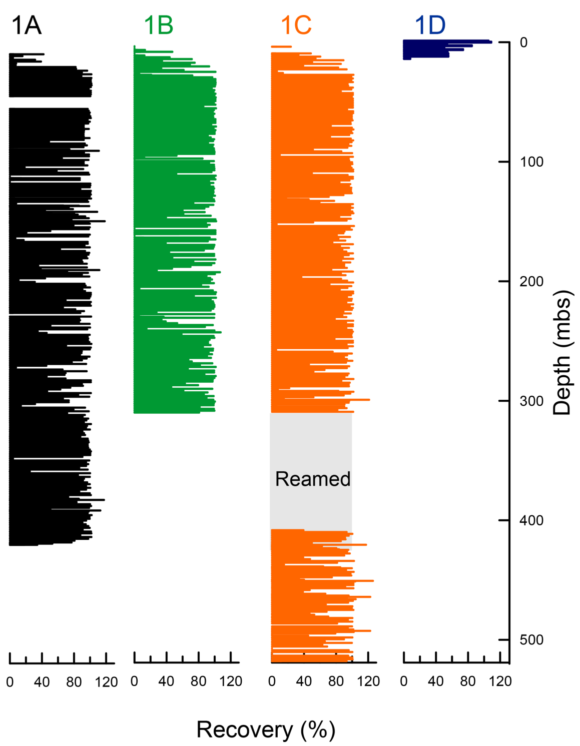

Figure 7. Core recovery from holes 1A, 1B, 1C, and 1D.

variations (cycles). This is also depicted in a wavelet analysis plot (Fig. 6), showing that variability in the range below ~ 10 m is quite consistent throughout the upper 300 m. In contrast, longer cycles are dominantly present in the lower interval from ~ 150 to 300 m depth. The magnetic susceptibility responds primarily to volcanic material in this location. As a result, it is generally low above ~ 250 m, with few spikes reflecting volcanic events (tephra layers or aquatic influx of volcanic material). The increase in resistivity and velocity reflects the higher degree of compaction with increasing depth.

4 Outreach and education

Outreach and education efforts in conjunction with the MexiDrill program succeeded in making the project known to members of the general public and providing coring-related educational activities to primary and secondary school children. We developed a logo by providing input to an online design firm (https://thelogocompany.net/, last access: 20 January 2016); we use this logo consistently across presentations and social media and have made stickers to distribute in Mexico, the US, Spain, and Germany to participating institutions, outreach events, and scientific meetings. The project Facebook page has over 600 followers, two-thirds of whom are from Mexico. We also developed a custom field trip in both English and Spanish for the NSF-funded Flyover Country mobile app for geoscience (https://flyovercountry.io/, last access: 5 June 2019) that includes the drilling site, information about the goals and successes of the project, and numerous local geological attractions in the Chalco area. The sites on this field trip are discoverable by anyone using Flyover Country to investigate the Mexico City region; the app has over 200 000 downloads. In collaboration with a UNAM faculty member, Ane María Soler, we developed an engaging activity ("coring" layers of red polymer or gelatin) for local primary school students, along with a Spanish language presentation about the MexiDrill project; the activity and presentation have been used with hundreds of additional students in the time since the drilling took place. Finally, the project benefited tremendously by building on many years of

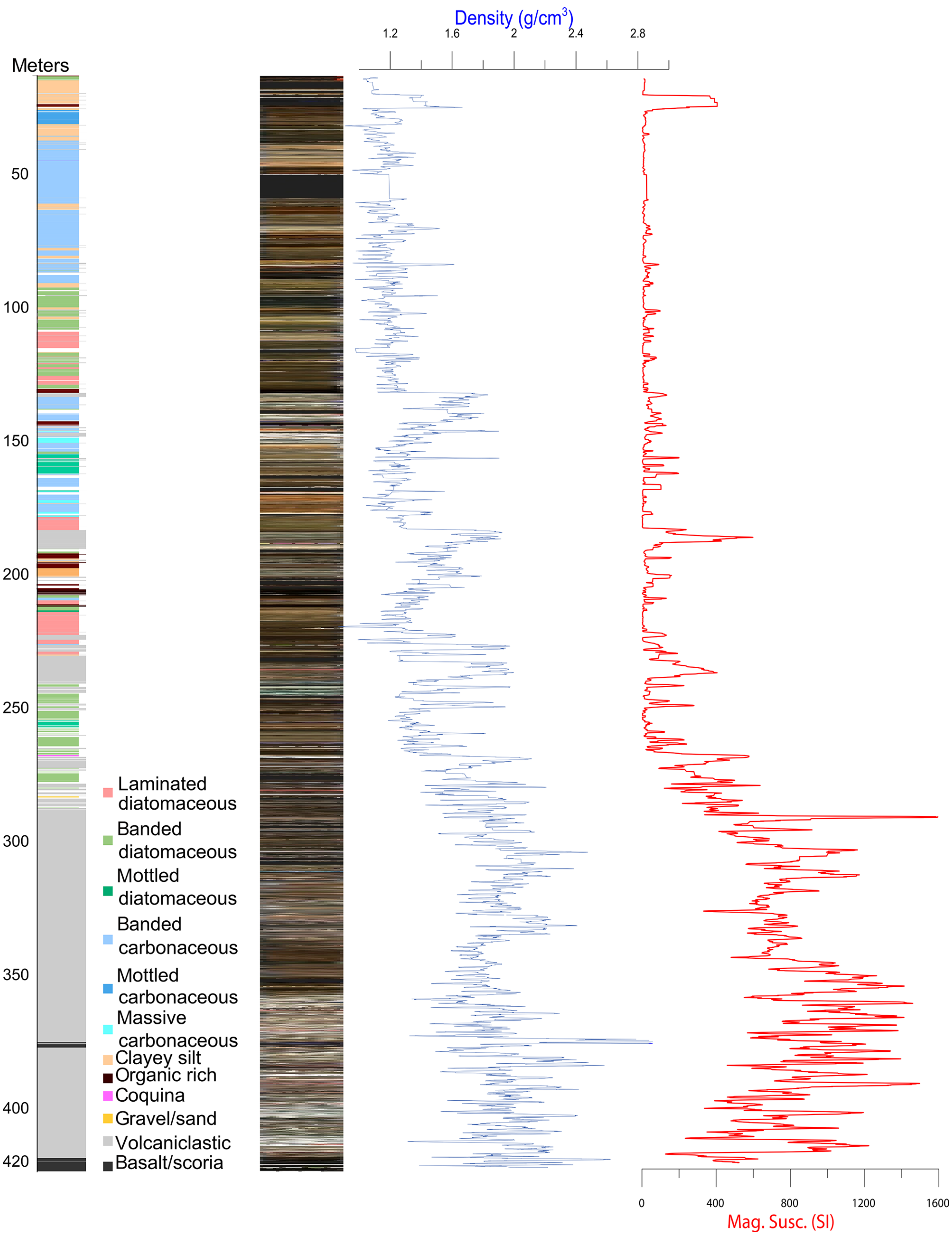

Figure 8. Selected results from the initial core description of MEXI-CHA16-1A, including lithology, color, density, and magnetic susceptibility. The broad shifts from diatomaceous to carbonaceous sediments are possibly associated with glacial–interglacial cycles, with relatively wetter times associated with Northern Hemisphere glaciation.

discussions between the UNAM faculty (Caballero, Lozano, Ortega, and others) and community leaders of the *ejidos*, communal agricultural land that surrounded the drilling site.

5 Initial core description results

Initial core description (ICD) was undertaken in the summer and fall of 2016. After whole-core multisensor logging (Geotek Multisensor Core Logger) for gamma density, acoustic wave velocity, electrical resistivity, loop-sensor magnetic susceptibility, and natural gamma cores were split lengthwise into work and archive halves. The core faces were cleaned for optical imaging, split-core multisensor logging with high-resolution point sensor magnetic susceptibility and color reflectance spectrophotometry, lithologic description of the archive half, and subsampling of the work half. Lithologic description included both visual core description (texture, bedding, color, structure, and other features) and petro-

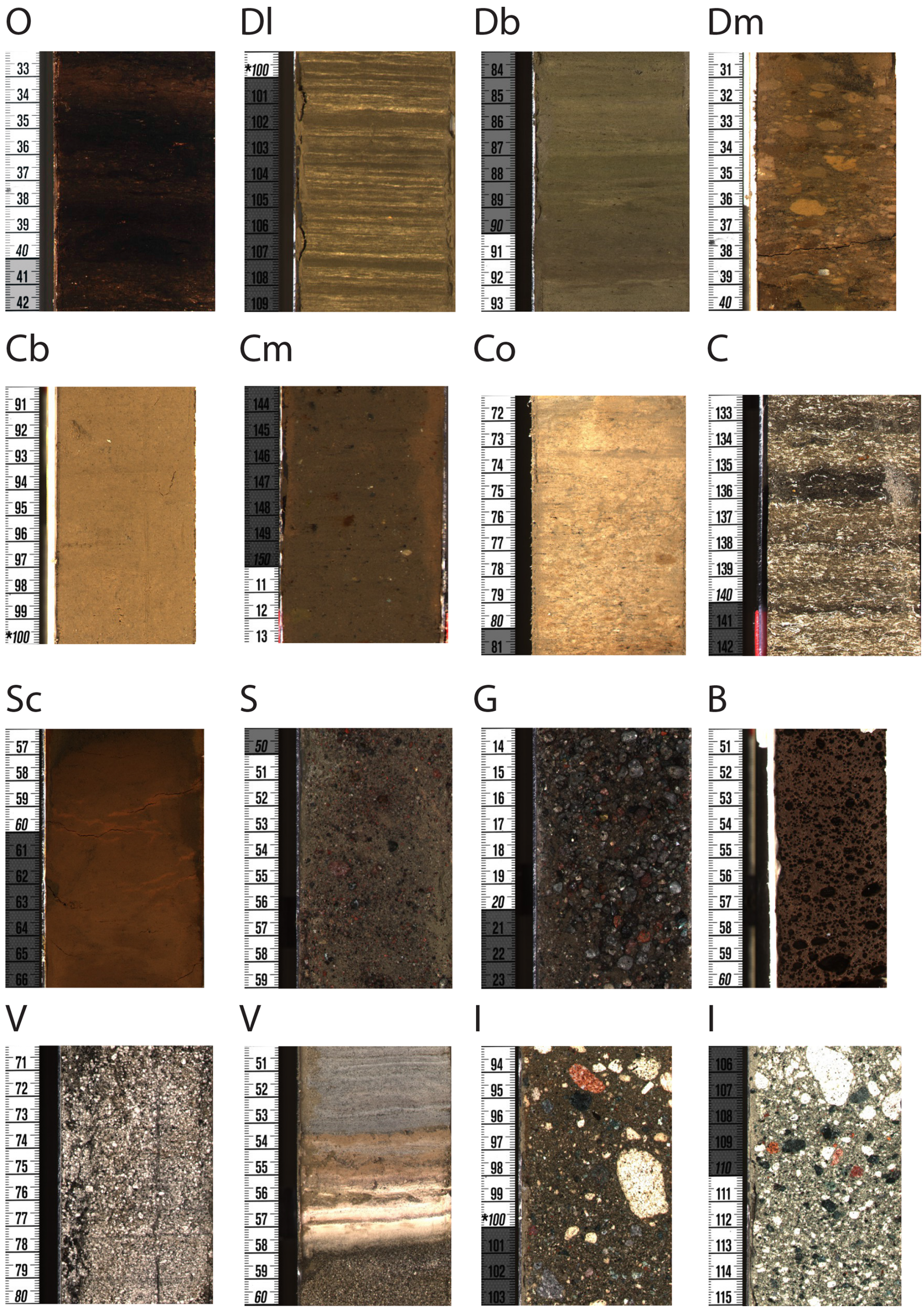

Figure 9. Representative lithologies. These include organic-rich sediments (O; MEXI-CHA16-1A-76Y-1 32–42 cm) including organic-rich silty clays, sapropelic silty clays, and peat; diatomaceous silty clays, which may be laminated (Dl; MEXI-CHA16-1C-140Y-1 99–109 cm), banded (Db; MEXI-CHA16-1A-169Y-1 83–93 cm), and mottled (Dm; MEXI-CHA16-1D-10C-2 30–40 cm); calcareous silty clays, which may be banded (Cb; MEXI-CHA16-1D-11C-13 90–100 cm), mottled (Cm; MEXI-CHA16-1B-14Y-1-A 143–153 cm), or massive (Co; MEXI-CHA16-1C-174Y-1 132–142 cm); gastropod-dominated coquina (C; MEXI-CHA16-1C-174Y-1 132–142 cm); clastic sediments including silty clays (Sc; MEXI-CHA16- 1A-27Y-1-A 56–66 cm), sand (S; MEXI-CHA16-1C-178Y-1 49–59 cm), and gravel (G; MEXI-CHA16-1C-182Y-1 13–23 cm); basalt (B; MEXI-CHA16-1C-231Y-1 50–60 cm); volcaniclastic deposits including pyroclastic flows, lahars, and reworked volcanics (V; MEXI-CHA16-1B-181Y-1 70–80 cm and MEXI-CHA16-1B-177Y-1 50–60 cm); and igneous rock composed of massive cemented volcanic rocks (I; MEXI-CHA16-1A-269Y-1-A 93–103 cm and MEXI-CHA16-1A-271Y-1-A 105–115 cm).

graphic smear slide and coarse fraction analysis for mineralogy and other microscopic constituents.

A splice (composite core) was developed from the four 2016 cores and portions of drill cores recovered through earlier shallow drilling campaigns in 2008 and 2011 at a site ∼ 450 m south-southwest of the 2016 drill site (Torres-Rodríguez et al., 2015; Herrera-Hernández, 2011). Metadata for the splice follow standard IODP protocols using splice and affine tables. An initial core stratigraphy was developed, and is summarized, along with logging data in Fig. 8.

Lithotypes were defined based on lithologies and textures determined by macroscopic examination and microscope smear slide observations. The broad range of depositional environments is reflected in the variety of lithotypes present in the core (Fig. 9).

6 Conclusions

The cores recovered by the MexiDrill project will provide information on the history of climate, environmental change, and volcanism over the past ∼ 400 kyr. In particular, the Chalco Basin is sensitive to changes in evaporation–precipitation balance that will provide key perspectives for evaluation of the impact of ongoing climate change on water resource availability in the Mexico City region.

Changes in hydrological balance are being evaluated using a combination of proxies based on sedimentology and sediment composition (e.g., carbonate preservation), pollen and diatom records, and the stable isotope composition of bulk OM, carbonates, diatom silica, and leaf waxes. XRF core scanning provides insights into carbonate deposition (Ca), diatom abundance (Si : Ti), and weathering intensity/sediment provenance (K : Ti). Variations in temperature will be examined through terrestrial and aquatic biomarkers in conjunction with pollen and microfossil records.

We will test the hypothesis that climate change drove the observed variations in glaciation by assessing the relative contribution of temperature (as measured by biomarkers) and precipitation (stable isotopes) to the change in glacial extent. An alternative hypothesis is that lake levels at Chalco responded to changes in basin morphology caused by volcanic activity (Siebe et al., 2017). For example, it is possible that MIS 2 appears less humid than MIS 6 and 8 in the Chalco record because topographic changes, associated with volcanism just north of Chalco (Sierra de Santa Caterina), decreased water flow from Chalco to the rest of the BoM lake system to the north and effectively made Chalco a closed-basin lake. We will evaluate this alternative by analyzing H isotopes in aquatic biomarkers to investigate potential shifts from open- to closed-basin hydrology (perhaps as a consequence of volcanic activity) and compare these results with broad-scale changes in precipitation inferred using H isotope analysis of terrestrial biomarkers, as well as through evidence from the volcanic deposits present in the core.

Extrapolation of radiocarbon-based sedimentation rates (Lozano-García et al., 2015) suggests that the Chalco record extends to MIS 9, which allows comparison of the regional response to precessional forcing during a warm interglacial (MIS 5e) with the response during cooler interglacials (MIS 7c and 7e). We will address this hypothesis using time series analysis of lake-level reconstruction and other proxies, including isotopes (biomarker δD, diatom δ^{18}O, carbonate δ^{18}O) and vegetation response (biomarker distributions and pollen abundance). If lake level/precipitation does not vary on precessional scales, it is difficult to argue that this pattern of greater precipitation during increased regional insolation would operate on a millennial scale. We will evaluate the relative influences of Northern Hemisphere ice sheets, insolation, and CO_2 on precipitation in central Mexico using band pass filtering and spectral analysis of these proxy records.

Data availability. Preliminary data outlined in this report are not publicly available as they are still being evaluated by the MexiDrill project team. Fully vetted datasets from the MexiDrill cores will be made available through LacCore, the National Lacustrine Core Repository, consistent with NSF and ICDP data sharing policies.

Sample availability. The archive and working halves of the MexiDrill (CHA16) cores are stored at LacCore (http://lrc.geo.umn.edu/laccore/repository.html; Noren, 2019).

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Competing interests. The authors declare that they have no conflict of interest.

Disclaimer. Any opinions, findings, or conclusions of this study represent the views of the authors.

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Coring the sedimentary expression of the early Toarcian Oceanic Anoxic Event: new stratigraphic records from the Tethys Ocean

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Abstract. The Toarcian Oceanic Anoxic Event (T-OAE) interval was cored at Colle di Sogno and Gajum in the Lombardy Basin (Southern Alps, northern Italy). The Sogno and Gajum cores recovered 26.83 and 31.18 stratigraphic metres, respectively, of pelagic sediments consisting of marly limestones, marlstone, marly claystone, and black shale. Drilling at both sites resulted in 100 % recovery of unweathered material. The pelagic succession comprises a relatively expanded black shale interval of 4.98 m in the Sogno core and 15.35 m in the Gajum core, with lower and upper boundaries without evidence of hiatuses. The Sogno and Gajum cores can be considered reference sections for the pelagic lower Toarcian interval of the western Tethys and will provide high-resolution micropaleontological, inorganic and organic geochemical, isotopic multiproxy data. Integrated stratigraphy and cyclostratigraphy are predicted to result in estimates of durations and rates to model the ecosystem resilience to the extreme perturbations of the T-OAE and gain a better understanding of current global changes and help provide better projections of future scenarios.

1 Introduction

The emergence of climate change as a crucial issue for society has urged the understanding of the future state of the planet within the context of increasing carbon dioxide concentrations. The ocean is the oldest ecosystem and the largest on Earth by volume and best records global changes in climate and atmospheric composition. Marine ecosystems are inextricably involved in the physical, chemical, biological processes of global change. In the near future, the ocean's uptake of CO_2 is expected to rapidly decline because of surface water warming, decreasing pH (acidification), increased vertical stratification, and slowed thermohaline circulation (Solomon et al., 2009). Consequently, a very rapid "in and out" from icehouse to greenhouse state – and vice versa – urges comprehension of positive and negative feedbacks on the biosphere.

Understanding of the Earth system at timescales longer than human observations has became imperative, because anthropogenic activities are likely to increase by orders of magnitude the rates of climatic change that usually result from natural processes. The Earth's ecosystems, thus, should be scrutinized on the medium- and long-term scales using geological records of past extreme environmental disturbances that exemplify varied tempos and modes of resilience, occasionally reaching tipping points that triggered permanent modifications.

The Toarcian Oceanic Anoxic Event (T-OAE) is the oldest Mesozoic case of global anoxia with widespread deposition of organic matter-rich sediments in a variety of depositional settings from continental to shallow- and deep-marine (Jenkyns, 1985, 1988, 2010). Available evidence suggests that at ~ 183 Ma the atmosphere and oceans experienced high CO_2, possibly due to the degassing of lava fields in the Karoo–Ferrar large igneous province and/or from dissociation and oxidation of methane hydrates in continental-margin sediments (Jenkyns, 2010) and/or terrestrial environments (Them et al., 2017). High atmospheric carbon dioxide possibly initiated greenhouse conditions that accelerated weathering and the hydrological cycle, increasing nutrient recycling into the oceans.

Although the original definition of the T-OAE was based on the presence of a lithostratigraphic marker (Jenkyns, 1985), the development of chemostratigraphy demonstrated that the T-OAE is associated with a negative C isotopic anomaly documented in marine carbonates and organic matter as well as in terrestrial organic matter including fossil wood and specific organic compounds (Jenkyns and Clayton, 1986; Hesselbo et al., 2000, 2007; Schouten et al., 2000; Jenkyns et al., 2002; Emmanuel et al., 2006; Van Breugel et al., 2006; Al-Suwaidi et al., 2010; Caruthers et al., 2011; Izumi et al., 2012; Kafousia et al., 2014; Reolid, 2014; Xu et al., 2017; Them et al., 2017; Fantasia et al., 2018). As shown by Fantasia et al. (2018), such a negative C isotopic anomaly might have resulted from volcanogenic CO_2, thermogenic methane associated with metamorphism, and dissociation of marine or terrestrial clathrates.

The T-OAE is further marked by an Os anomaly (Cohen et al., 2004; Percival et al., 2016; Them et al., 2017), biocalcification crisis (Erba, 2004; Mattioli et al., 2004; Casellato and Erba, 2015; Erba et al., 2019), increased primary productivity (Jenkyns, 2010; Erba, 2004), and ocean acidification (Erba, 2004; Trecalli et al., 2012; Casellato and Erba, 2015; Posenato et al., 2018), which occurred during an exceptional warming phase (Dera et al., 2011; Korte and Hesselbo, 2011; Gómez et al., 2016) and a major transgression (e.g. Haq et al., 1987; Hardenbol et al., 1998).

Jurassic pelagic successions in the Southern Alps have been extensively investigated for stratigraphy, sedimentology, paleontology, and geochemistry (Bernoulli and Jenkyns, 2009; Erba et al., 2019). In particular, multi- and interdisciplinary studies have demonstrated that the Jurassic pelagic successions of the Lombardy Basin represent "type-sections" of the Tethyan southern margin (Gaetani, 2010). Indeed, the Lombardy Basin is part of the relatively undeformed portion of Adria interpreted as an African "promontory" or as a microplate (Fig. 1). In the latest Triassic–earliest Jurassic a rifting phase caused the breakup of carbonate platforms into a series of "horst and graben" that exerted a physiographic control on sediment type and distribution for most of the Jurassic (Bernoulli and Jenkyns, 1974, 2009; Bosence et al., 2009; Santantonio and Carminati, 2011). As a consequence, sedimentation was differentiated with the deposition of thick complete pelagic successions in the deeper zones, while sedimentation was typically condensed and incomplete on the structural highs.

During the Jurassic the Lombardy Basin was globally a deep area between the Lugano High to the west and the Trento Plateau to the east (Fig. 1). However, the latest Triassic–earliest Jurassic rifting disentangled a number of troughs and paleohighs that are as follows, from west to east: Monte Nudo Trough, Lugano High, Generoso Trough, Corni di Canzo High, Albenza Plateau, Monte Cavallo High, Sebino Trough, Botticino High (Gaetani, 1975, 2010). In the troughs, partially resedimented Lower Jurassic marlstone–limestone sequences may reach a non-decompacted thickness of 3000 m (e.g. in the Generoso Trough), but condensation and hiatuses characterize the paleohigh sections with reddish nodular facies. Along slopes connecting structural highs to the troughs, sedimentation was marked by slumps, resedimented bodies, and, locally, megabreccias within condensed and occasionally incomplete facies (Gaetani and Erba, 1990; Gaetani, 2010) (Fig. 1). In addition to regional tectonics, the Lombardy Basin successions record global climatic and oceanographic changes, including the T-OAE (Erba et al., 2019). In fact, lower Toarcian black shales have been documented in various sections, offering the opportunity to investigate the consequences of the T-OAE global changes on marine biota in the Tethys Ocean (Erba et al., 2019).

After close investigations of section outcropping in the Lombardy Basin, the Colle di Sogno and Gajum sites were selected as the most promising locations for continuous coring of pelagic records (Gaetani and Erba, 1990; Casellato and Erba, 2015) for continuous coring. In this paper, we document coring operations and lithostratigraphic characterization of both the Sogno and Gajum cores and outline ongoing multidisciplinary research.

2 Coring through the sedimentary record of the early Toarcian Oceanic Anoxic Event

The T-OAE is considered a natural Earth system experiment, which allows us to (a) detect and quantify processes associated with emissions of greenhouse gases and natural atmospheric pollutants; (b) understand the role of greenhouse gases on climate dynamics and its influence on the hydrological cycle; (c) characterize changes in ocean and atmospheric chemistry and their interactions; (d) assess changes in biodiversity and dynamics of ecosystems and understand the functioning of biotic sinks; and (e) quantify biosphere–geosphere–atmosphere interactions and their timings or rates.

Analysis of past global change requires the collection of high-resolution data from continuous and ideally unweathered sequences. In surface outcrops, sedimentary rocks and particularly black shales are commonly badly degraded and, consequently, drilling is crucial to ensure the recovery of high-quality fresh cored material. In this paper we identify the T-OAE adopting the original definition by Jenkyns (1985) based on lithostratigraphy. Therefore, the T-OAE in the Lombardy Basin corresponds to the Livello a Pesci (Tintori, 1977; Gaetani and Poliani, 1978; Erba and Casellato, 2010; Erba et al., 2019). This interval has an average thickness of 0.5 to 5 m, but reaches a few tens of metres in the most expanded sections. Black shales are rarely recorded on paleohighs, whereas they are ubiquitous in deeper basins. As the T-OAE occurred at a global scale, the local lack of black shales

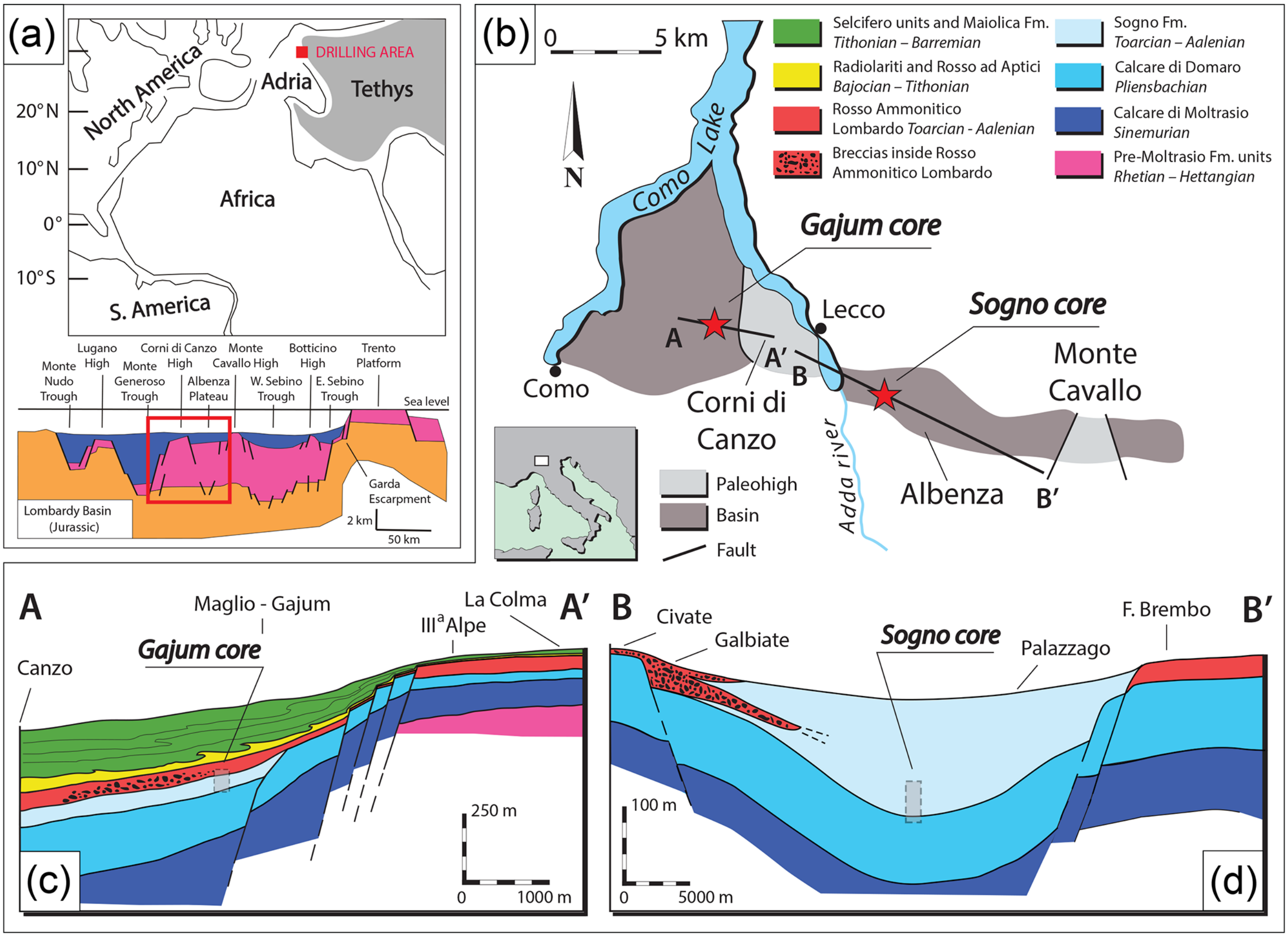

Figure 1. Location of the Sogno and Gajum drilling sites relative to **(a)** paleogeography and **(b)** current geography. The drilling area was part of the Lombardy Basin (Southern Alps). **(c)** The Gajum core is sited in an inner basin along the western slope of the Corni di Canzo High while **(d)** the Sogno core was drilled on the Albenza Plateau as detailed in the geological sections in the lower part of the figure (modified after Gaetani and Poliani, 1978 and Gaetani and Erba, 1990).

in the Lombardy Basin is usually the result of condensation and/or stratigraphic gaps.

Location of the drill sites and justification for coring

Two Lower Jurassic sections at Colle di Sogno and Gajum, respectively, were selected for continuous coring through the Toarcian organic-rich black shale interval (Fig. 1). Within the Lombardy Basin, these sections represent significantly different geological settings on a pelagic structural high, namely the Albenza Plateau (Colle di Sogno) and in an inner basin along the slope of the Mt Corni di Canzo structural high (Gajum) (Gaetani and Erba, 1990; Gaetani, 2010). Both successions are relatively expanded and lack the diagenetic manganese–carbonate horizons (present in the Toarcian black shales of the Belluno Basin, Southern Alps, for example) that would compromise primary geochemical signatures (Farrimond et al., 1988; Jenkyns, 1988; Jenkyns et al., 1991; Bellanca et al., 1999).

The Colle di Sogno site (Fig. 1) was selected because the Jurassic sequence exposed is pelagic, stratigraphically continuous and relatively expanded (Gaetani and Erba, 1990; Muttoni et al., 2005; Channell et al., 2010; Casellato and Erba, 2015). It consists of limestone and marlstone, with chert and marly claystone as minor lithologies. The T-OAE is here represented by ∼ 5 m of dark grey to black marly claystones of the Livello a Pesci. At Colle di Sogno, the type-section of the Sogno Formation (Gaetani and Poliani, 1978), located along the road SP 179 on the northern slope of Mt Brughetto, was proved to be suitable for high-resolution multidisciplinary studies of litho-, bio-, chemo-, magneto-, and cyclo-stratigraphy (Gaetani and Poliani, 1978; Jenkyns and Clayton, 1986; Gaetani and Erba, 1990; Hinnov et al., 2000; Channell et al., 2010; Casellato and Erba, 2015).

The Gajum succession crops out in a small lateral cut of the Ravella valley (Fig. 1), where the basal lithofacies of the Moltrasio Limestone Formation suggests sedimentation in shallower water than on the Albenza Plateau (Gaetani and Poliani, 1978; Gaetani and Erba, 1990; Pasquini and Vercesi, 2002). In particular, slumps and resedimented bodies with an eastward-sliding direction document a constant instability of the ramp, indicating that the succession developed in a small inner basin separated by a sill from a deeper basin to the west (Pasquini and Vercesi, 2002). A sharp lithological change marks the boundary between the carbonate-rich lithologies of the Domaro Limestone Formation and the overlying clay-rich lithologies of the lower Sogno Formation consisting of marlstones and marly limestones followed by reddish nodular limestones of the Rosso Ammonitico Lombardo. At Gajum the expanded nature of the black shale interval (∼ 15 m) offers the opportunity for studying the inception, evolution, and termination of the T-OAE in great detail.

3 Drilling operations and lab core preparation

The Sogno drilling campaign took place in June 2013, while the Gajum core was drilled in February 2016 (Fig. 2). At both Sogno and Gajum sites, drilling operations were performed with the DELTABASE 520 Modular Hydraulic Rotary Drill. The Sogno coring was accomplished with a T2 double corer, using narrow-kerf, sawtoothed drill bits that cut a 101 mm diameter borehole and 84 mm diameter cores. The Gajum core was obtained using a modified T6 triplex corer, including a plastic liner for the best recovery, using narrow-kerf, sawtoothed drill bits that cut a 131 mm diameter borehole and 101 mm diameter cores. At Gajum, after coring, the borehole was logged using a QL40-OBI optical televiewer to obtain high-resolution images of the borehole wall, together with a total gamma radiation tool (Fig. 3).

All cores were initially described on site and a preliminary log was produced. Then, cores were packed, labelled, and put in PVC plastic boxes to prevent contamination and transported to the Department of Earth Sciences in Milan where they are archived. Here, during lab preparation, all cores were longitudinally split along the dip and divided into an archive half and a sampling half, both marked at centimetre scale. The archive half was photographed in high resolution and composite photologs were produced for each site.

4 Preliminary results

4.1 Lithostratigraphy of the Sogno core

Four distinct boreholes (S1, S2, S3, and S4) were drilled at Colle di Sogno along the SP 179 road (45°47′20.5″ N, 9°28′30.0″ E). The outcropping beds show a strike of 150° and a dip of 68° to the southwest (240°).

Initially, a single borehole was planned to penetrate the lower Toarcian–uppermost Pliensbachian interval and reach the base of the Sogno Formation at ∼ 35 m penetration depth. However, at ∼ 25 m penetration depth (core S1-27) a sharp dip increase to 88° revealed the occurrence of a fold, partially faulted and reversed, persisting for ∼ 4 m (cores S1-27, S1-28, and S1-29). Indeed, core S1-30 perfectly correlates with the lower part of core S1-26 and two black shales were used as lithostratigraphic markers. Coring was extended for ∼ 2 m (cores S1-31 and S1-32) penetrating the top of the black shale interval and then operations were interrupted to shift drilling to borehole S2 (Fig. 4). Due to the steep dip, it was decided to perform a 10° inclined coring to decrease the total penetration depth down into the Domaro Limestone Formation. Borehole S2 started just above the top of the black shale interval of the Livello a Pesci, perfectly duplicating core S1-32. However, technical problems prevented coring below a few metres and operations stopped after recovery of core S2-3. The third borehole (S3) was moved 0.5 m relative to S2 and was cored vertically. Again, the recovered succession started from just above the top of the black shale interval with core S3-1 triplicating cores S1-32 and S2-1. Coring was extended to 40 m penetration depth, reaching the uppermost part of the Domaro Limestone Formation (Fig. 4). A fourth borehole (S4) was performed to duplicate the middle and lower portion of the black shale interval to ensure material for multidisciplinary investigations. The recovery percentage for the four boreholes is 99.9 %.

Lithostratigraphic units were defined on the basis of lithological features (i.e. lithology and colours determined with the Munsell Rock Color Chart) and sedimentary structures (i.e. presence or lack of bioturbation and/or lamination). For each core at least four dip measurements were taken during lab preparation to calculate the stratigraphic thickness of the drilled section as 25.33 m under 1.5 m of rubble at the top. A complete composite section, representing the upper Pliensbachian–lower Toarcian interval, was created by combining the data obtained from the S1 and S3 boreholes (Fig. 5). The following key observations were derived:

1. The first 1.5 m of the S1 borehole are represented by soil cover and rubble.

2. The S1 core, despite the occurrence of a faulted fold disturbing the succession, recovered a complete section above the Livello a Pesci. The bottommost part of the well reached the uppermost part of the black shale interval. This correlates with the top black shale interval recovered in the upper part of the S3 core.

3. The upper limit of the black shale interval was cored both at S1 and S3 sites.

4. The S3 core recovered a few metres of succession above the black shale interval, the entire Livello a Pesci, and the lower portion of the Sogno Formation, in addition to the topmost part of the Domaro Limestone. In particular, at 25.47 m, the lithostratigraphic boundary between

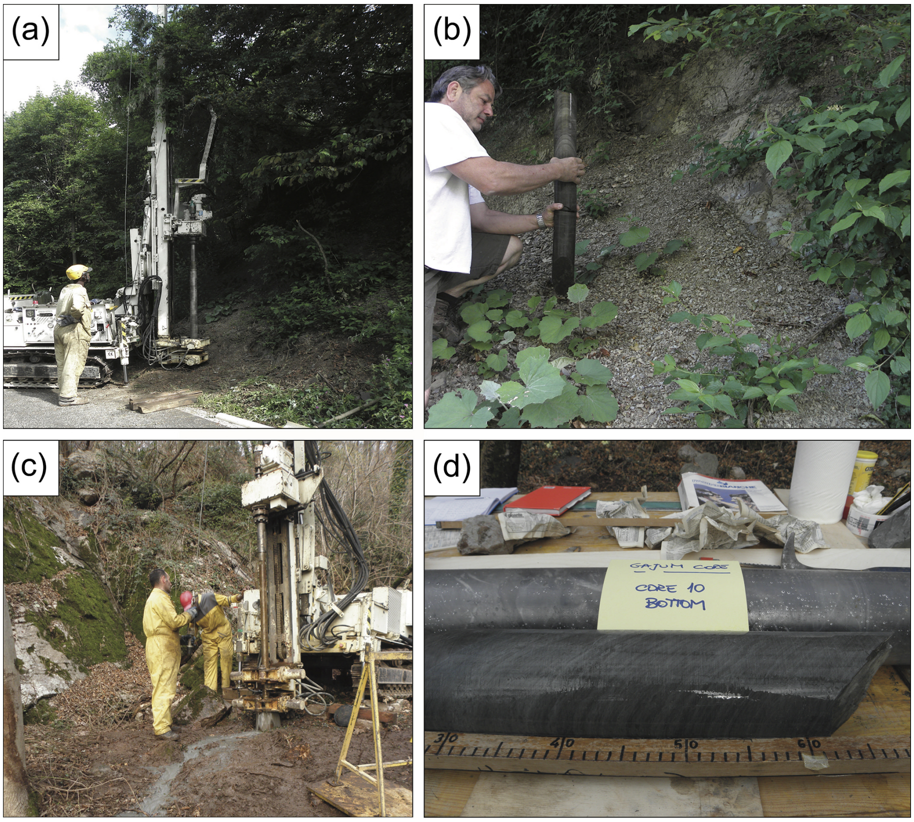

Figure 2. Coring operations and results at Sogno and Gajum sites. **(a)** Coring Sogno Site 4. **(b)** Livello a Pesci in the Sogno core compared to the equivalent outcropping lithostratigraphic interval. **(c)** Coring at Gajum. **(d)** Black shale interval recovered in core 10 of the Gajum core.

the Sogno Formation and Domaro Limestone Formation was recovered.

Combining the above information and considering the dip measured in individual cores (variable in the range of 60 to 87°), the "stratigraphic thickness" of each lithostratigraphic unit was calculated. The overlapping intervals (i.e. U1-5 and U3-1) were matched and duplications were eliminated. The lithologic log of the composite S1–S3 Sogno core, in stratigraphic depths (from 1.5 to 26.83 m), is illustrated in Fig. 5. The composite S1–S3 Sogno core section recovered a complete upper Pliensbachian–lower Toarcian interval, with the S1 core representing its upper portion, and the S3 core the lower part.

The following lithostratigraphic units (U1-1 to U1-5, and U3-2 to U3-11, of the S1 and S3 cores, respectively) are described, from the topmost to the bottommost:

- *Unit 1 (1.50 to 4.82 m): marly limestones, olive-grey in colour*. In the upper and lowermost parts of the unit, high concentrations of reddish mottles and sporadic bioturbation are documented.

- *Unit 2 (4.82 to 9.54 m): marly limestones, olive-grey in colour, characterized by intense bioturbation*. In particular, the uppermost part of the unit documents the presence of frequent *Planolites*.

- *Unit 3 (9.54 to 10.52 m): marly limestones, grey in colour, characterized by intense bioturbation*. Locally, faintly laminated intervals are observed.

- *Unit 4 (10.52 to 11.87 m): marly limestones with evident and widespread bioturbation*. Locally, 1 to 6 cm thick black shales and laminated intervals are present.

- *Unit 5 (11.87 to 14.55 m): black shales characterized by well-developed lamination, especially in the uppermost part, in addition to pyrite nodules*. In the lower portion, very little bioturbation is documented.

- *Unit 6 (14.55 to 15.93 m): marly limestones, grey to very dark-grey in colour, with reddish to greyish spots*. Bioturbation (burrow) dimensions increase within this unit and thin emerald-green laminae are documented.

- *Unit 7 (15.93 to 16.86 m): marly limestones, with variations in colour from grey, to very dark-grey and dark-red*. In the lowermost portion, bioturbation and lamination are observed.

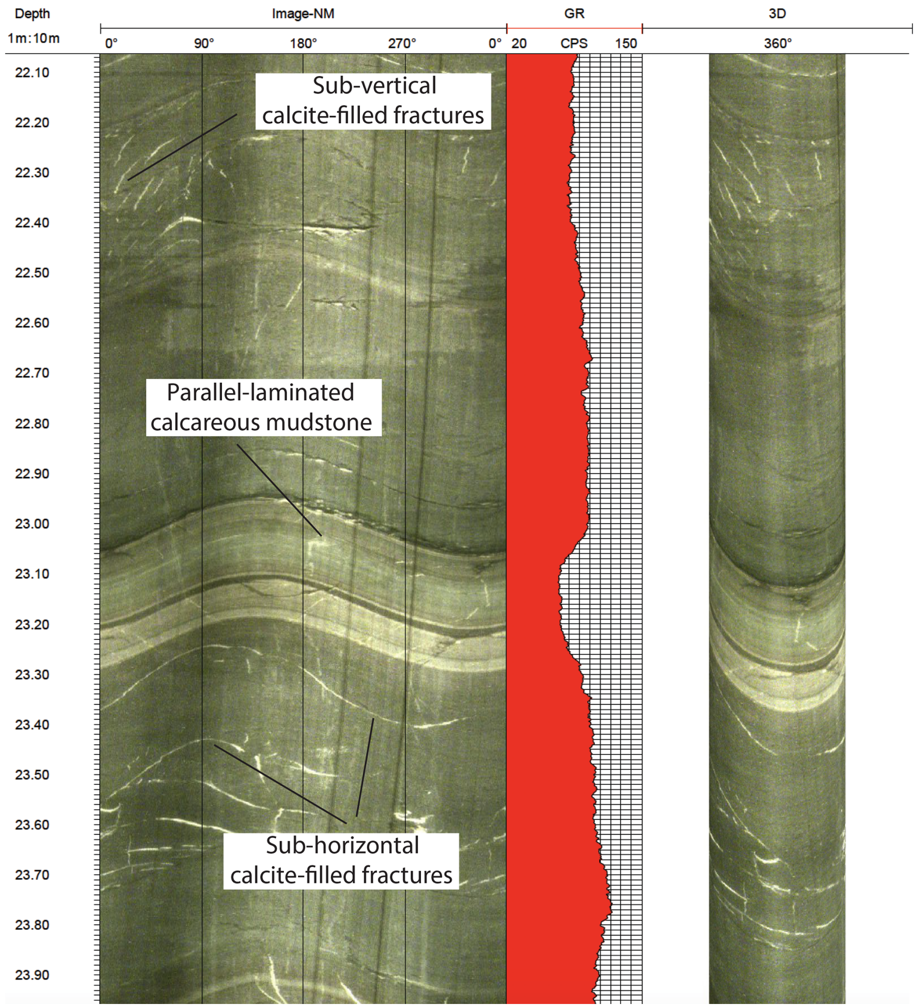

Figure 3. Example of Gajum borehole wall image recorded with a QL40-OBI optical televiewer. From left to right: borehole depth, 360° continuous upwrapped digital image of the borehole wall, total natural gamma ray, 3-D log visualization reproducing a virtual core of the borehole.

- *Unit 8 (16.86 to 19.10 m): marly limestones, dark-red in colour, with sporadic greyish spots.*
- *Unit 9 (19.10 to 19.45 m): marly limestones, grey in colour.*
- *Unit 10 (19.45 to 21.35 m): marly limestones, grey-brown in colour*. This is a disturbed interval comprising a level of pebbly marlstones (between 19.45 and 20.03 m), with minor slump structures. Sporadic stylolites are present.
- *Unit 11 (21.35 to 22.92 m): marly limestones, grey in colour, characterized by frequent stylolite structures*. In addition, 2 cm thick black shale intervals are documented at ∼ 21.8 and 22 m, respectively.
- *Unit 12 (22.92 to 24.35 m): marly limestones, alternating in colour from reddish to olive-grey*. Sporadic bioturbation and lamination can be observed.
- *Unit 13 (24.35 to 24.99 m): marly limestones, reddish-greyish in colour.*

  Unit 14 (24.99 to 25.47 m): marly limestones, light-brown to grey-brown in colour. Small and large (1 cm thick) burrows are documented. The base of this unit corresponds to the base of the Sogno Formation.
- *Unit 15 (25.47 to 26.83 m): marly limestones, olive-grey to dark-grey in colour*. Small bioturbations and frequent stylolite structures are observed. This unit corresponds to the uppermost part of the Domaro Limestone Formation.

4.2 Lithostratigraphy of the Gajum core

The Gajum core (45°51′03.2″ N, 09°17′19.5″ E, at 555 m above sea level) was drilled close to "Fonte Gajum" – Canzo (CO), in the Ravella valley next to the trail named Via delle

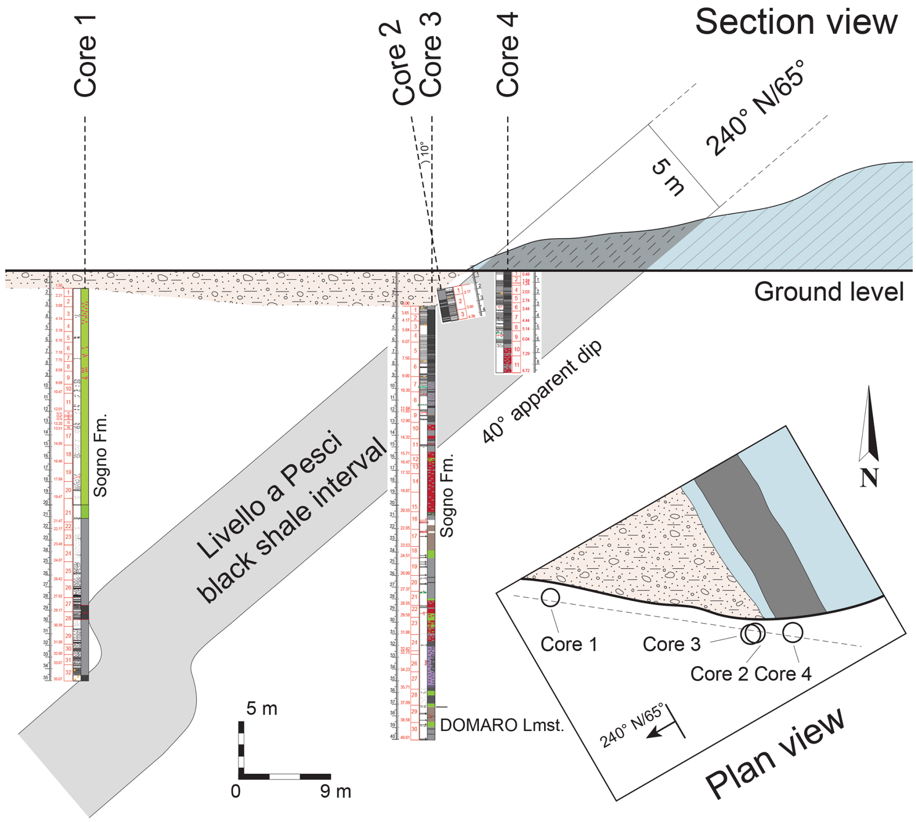

Figure 4. Section and plan view of the relative positions of the four boreholes drilled at Colle di Sogno. A pronounced fold was encountered at ∼ 25 m penetration depth in Sogno borehole 1 that was abandoned after reaching the topmost part of the black shale interval. Three additional boreholes were cored as explained in the text.

Alpi (Fig. 1). The outcropping beds show a strike of 245° and a dip of 46° to the northwest (335°).

A single borehole was drilled at Gajum to a total penetration depth of 42.37 m, with 100 % recovery of excellent-quality material throughout drilling operation. For each core a set of dip measurements was taken during lab preparation, with four measurements on average, and used to calculate the corrected thickness of the drilled section as 28.18 m after removal of 3 m of rubble at the top. As for the Sogno core, lithostratigraphic units were defined based on lithological features and sedimentary structures. The dip measured in individual cores (variable in the range of 40 to 50°) was used to calculate the "stratigraphic thickness" of each lithostratigraphic unit described below, from the topmost to the bottommost:

– *Unit 1 (3.00 to 4.35 m): dark brown to dusky red nodular limestone*. nodules are 3–5 cm in size and light grey in colour. A resedimented level, consisting of a microbreccia, is detected at 3.92–3.96 m. This unit corresponds to the lower part of the Rosso Ammonitico Lombardo.

– *Unit 2 (4.35 to 7.60 m): marly limestone, grey to olive grey in colour, with dark grey laminated intervals*. Three black shale intervals occur at 5.24–5.35, 6.26–6.43, and 6.70–6.81 m.

– *Unit 3 (7.60 to 10.60 m): grey to dark grey marly limestone, with heavily bioturbated levels alternating with intervals characterized by faint lamination*. Some pyrite nodules are observed in the lowermost part of the unit.

– *Unit 4 (10.60 to 21.39 m): dark to very dark grey to black marly claystones*. This "black shale" interval is characterized by well-developed lamination and frequent pyrite nodules. In the upper and middle portion, discrete intervals with faint bioturbation are observed.

– *Unit 5 (21.39 to 25.42 m): dark to very dark grey to black marly claystones characterized by well-developed lamination and a few pyrite nodules*. Three intervals of dusky red limy cherts are identified at 21.39–21.87, 23.52–23.81, and 24.30–25.52 m. The highest and lowest cherty reddish levels delimit the top and bottom of this unit, respectively.

– *Unit 6 (25.42 to 26.95 m): dark grey to very dark grey to black marly claystones, with evident laminations and sporadic faint bioturbations*. The base is undulated.

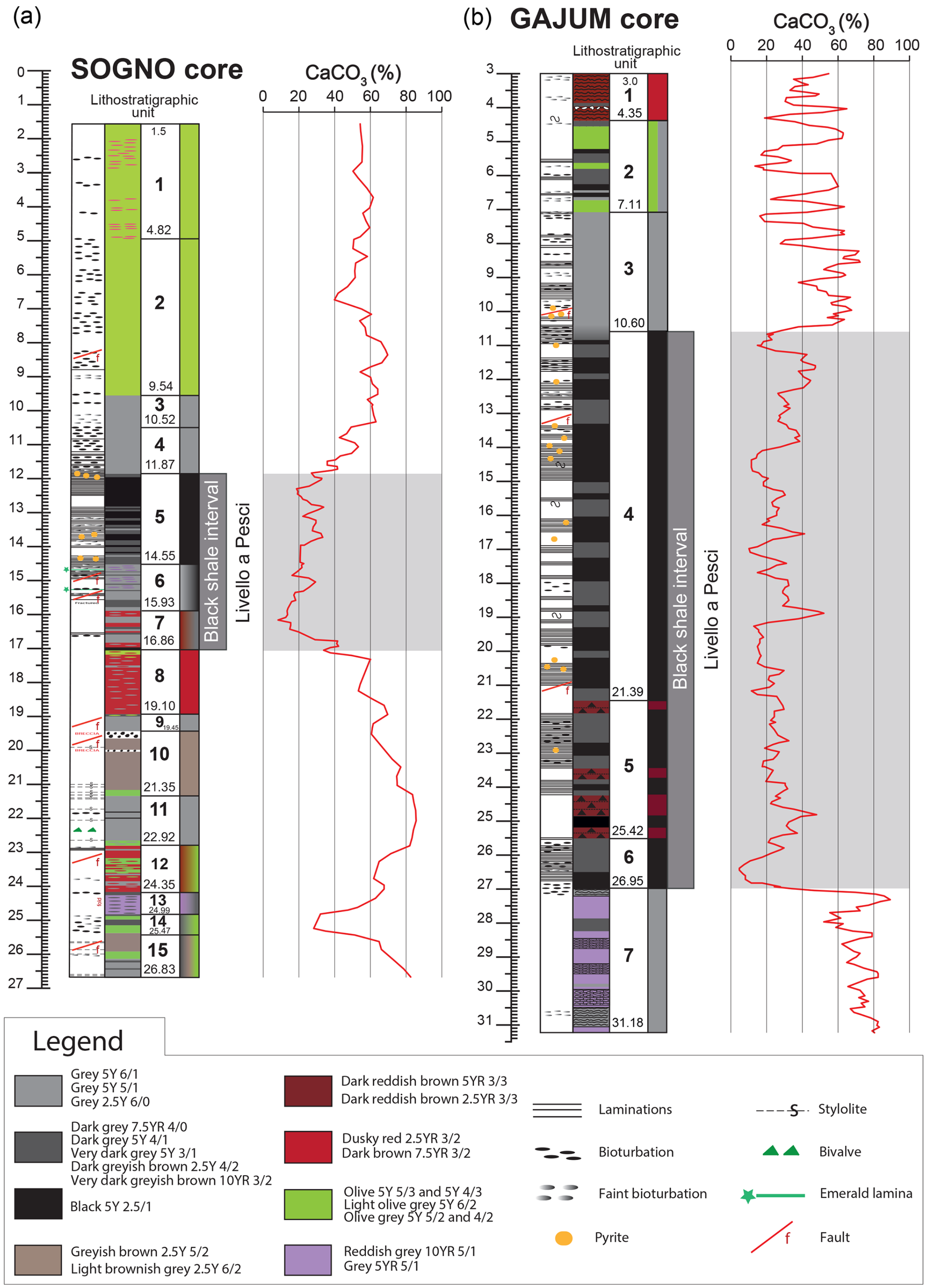

Figure 5. Lithostratigraphy and calcium carbonate content of the Sogno **(a)** and Gajum **(b)** cores. The grey pattern highlights the Livello a Pesci black shale interval that is the lithostratigraphic record of the T-OAE in the Lombardy Basin. The $CaCO_3$ content was detected using the Dietrich-Frühling gas volumetric method by measuring evolved CO_2 after acidification of the bulk sample with HCl.

– *Unit 7 (26.95 to 31.18 m): grey to reddish grey marly limestones, with fractures filled by diagenetic calcite.*

In Fig. 5 the Sogno and Gajum cores are correlated: the T-OAE black shale interval is represented in both sections, but with significantly different thicknesses, namely 4.98 m in the Sogno core and 15.35 m in the Gajum core. The lithostratigraphic onset and termination of the Livello a Pesci black shale interval, based on the lowest and highest black marly claystones, are nicely preserved in both cores, without lithologic evidence of hiatus or disturbance. In the Gajum core the beginning of the anoxic interval is quite abrupt and represented by the change from a few centimetres thick, grey, pseudonodular, and heavily bioturbated marly limestone to black shales with an irregular base mimicking nodularity of the underlying interval: this lithostratigraphic boundary is very similar to the onset of the early Aptian OAE1a in the Cismon core (Erba et al., 2010; Fig. 2). The upper boundary is, conversely, relatively transitional from laminated black shales to dark grey marly limestones. In the Sogno core, instead, both the base and top of the black shale interval are sharp.

The Livello a Pesci is not homogeneous in the Sogno and Gajum cores: in both records, the lower part is characterized by the occurrence of a few reddish levels. These are cherty in the Gajum core (Unit 5) and clayey in the Sogno core (Unit 7). Also, black shales are dominant in the upper part of the Livello a Pesci in both cores (Unit 4 of the Gajum core and Unit 5 of the Sogno core).

As far as the calcium carbonate content is concerned (Fig. 5) in the Sogno and Gajum cores, the interval below the Livello a Pesci is characterized by values of around 60 % and 60 %–80 % $CaCO_3$, respectively. A drop in calcium carbonate content to an average of 20 % is recorded within the black shale interval in both cores, with lowermost values of 5 % (Gajum core) to 10 % (Sogno core) in the lowermost part. Above the Livello a Pesci, the calcium carbonate content reverts to 40 %–60 %, with frequent fluctuations.

5 Future objectives

The fresh material recovered with the Sogno and Gajum cores provide complete and relatively expanded pelagic records from the western Tethys Ocean. Detailed multidisciplinary investigations are in progress to collect multi-proxy records for building a high-resolution dataset prodromic for modelling the nature and significance of the T-OAE. The specific objectives are as follows:

1. *High-resolution integrated stratigraphy*. This is based on nannofossil biostratigraphy, magnetostratigraphy, chemostratigraphy, and cyclostratigraphy. Milankovitch cycles will be used to estimate durations of the T-OAE.
2. *Detailed studies of critical paleoceanographic parameters*. This includes total organic carbon; isotopic anomalies; and major, minor and trace elements that will be used to assess changes in surface and bottom water mass characteristics.
3. *Identification and quantification of the response of the biosphere*. This is based on quantitative and high-resolution investigation of calcareous phytoplankton assemblages. In particular, we will focus on the relative timing and possible phase-lag of the response to the overwhelming forcing function/s. These relationships will be used to model the resilience of the oceanic biosphere.
4. *Characterization of the Early Jurassic climate, ocean dynamics, and their response to orbital cyclicity.*. In particular, we plan to decipher local from regional and global changes across the paleoenvironmental perturbation. Also, the cyclostratigraphy will allow for the assessment of the influence of eccentricity, obliquity, and precession cycles before, during, and after the T-OAE.

Data availability. The Sogno and Gajum cores are stored at the Department of Earth Sciences “Ardito Desio” of the University of Milan (Italy). Data are publicly accessible upon request.

Author contributions. EE conceived and executed the Sogno and Gajum coring. She coordinated the lab core work and prepared the paper. GG co-supervised the core description and contributed to the paper. Other co-authors (SV, LC, DR, GF, MP) contributed to core splitting, archiving, and sampling.

Competing interests. The authors declare that they have no conflict of interest.

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Scientific Drilling
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Workshop Reports

A roadmap for amphibious drilling at the Campi Flegrei caldera: insights from a MagellanPlus workshop

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Abstract. Large calderas are among the Earth's major volcanic features. They are associated with large magma reservoirs and elevated geothermal gradients. Caldera-forming eruptions result from the withdrawal and collapse of the magma chambers and produce large-volume pyroclastic deposits and later-stage deformation related to post-caldera resurgence and volcanism. Unrest episodes are not always followed by an eruption; however, every eruption is preceded by unrest.

The Campi Flegrei caldera (CFc), located along the eastern Tyrrhenian coastline in southern Italy, is close to the densely populated area of Naples. It is one of the most dangerous volcanoes on Earth and represents a key example of an active, resurgent caldera. It has been traditionally interpreted as a nested caldera formed by collapses during the 100–200 km^3 Campanian Ignimbrite (CI) eruption at ~ 39 ka and the 40 km^3 eruption of the Neapolitan Yellow Tuff (NYT) at ~ 15 ka. Recent studies have suggested that the CI may instead have been fed by a fissure eruption from the Campanian Plain, north of Campi Flegrei.

A MagellanPlus workshop was held in Naples, Italy, on 25–28 February 2017 to explore the potential of the CFc as target for an amphibious drilling project within the International Ocean Discovery Program (IODP) and the International Continental Drilling Program (ICDP). It was agreed that Campi Flegrei is an ideal site to investigate the mechanisms of caldera formation and associated post-caldera dynamics and to analyze the still poorly understood interplay between hydrothermal and magmatic processes. A coordinated onshore–offshore drilling strategy has been developed to reconstruct the structure and evolution of Campi Flegrei and to investigate volcanic precursors by examining (a) the succession of volcanic and hydrothermal products and related processes, (b) the inner structure of the caldera resurgence, (c) the physical, chemical, and biological characteristics of the hydrothermal system and offshore sediments, and (d) the geological expression of the phreatic and hydromagmatic eruptions, hydrothermal degassing, sedimentary structures, and other records of these phenomena. The deployment of a multiparametric in situ monitoring system at depth will enable near-real-time tracking of changes in the magma reservoir and hydrothermal system.

1 Introduction

Large collapse calderas are associated with climactic explosive volcanic eruptions capable of producing a global catastrophe second only to that from a meteorite impact. On the other hand, many calderas are characterized by hydrothermal systems that represent a source of "clean", geothermal energy production (e.g., Lipman, 2000). Despite numerous scientific and applied studies, the inner structure and the dynamics of caldera systems are still poorly known. In many cases, large calderas also host densely populated urban and agricultural districts. As a consequence, understanding the caldera structure and dynamics has an immediate effect on the assessment of volcanic hazards and associated risk at a local and global scale.

Large calderas are found on all continents and in different geological settings. For example, recent restless examples can be found in New Zealand (Taupo), North America (Crater Lake, Long Valley, Valles, Newberry, and Yellowstone), South America (Laguna de Maule and Cerro Blanco), Asia and Oceania (Toba, Tambora, Krakatau, Rabaul, Toya, Shikotsu, and Kuttara), and Europe (Santorini and Campi Flegrei). Some of these are located close to coastlines and continental shelves, where hydrothermal and groundwater dynamics may partly control the expression of volcanism and the distribution of eruptive products. Deposition of these products occurs in a changing depositional regime with a high average sedimentary supply. Coastal and partly submerged calderas on continental shelves thus contain unique stratigraphic archives of interbedded volcaniclastic and marine deposits with a high potential for preservation.

The Campi Flegrei caldera (CFc), next to Naples in southern Italy, has been the world's most restless, non-erupting caldera for the last 69 years, characterized by episodes of significant ground uplift, enhanced hydrothermal activity, and seismicity. In addition to these short-term episodes (e.g., 1950–1952, 1969–1972, and 1982–1984; De Natale et al., 2006; Del Gaudio et al., 2010; Troiano et al., 2011; Chiodini et al., 2015, 2017; Kilburn et al., 2017; Moretti et al., 2017, 2018), ground subsidence and uplift of several meters has been documented since at least Roman times (e.g., Bellucci et al., 2006; Di Vito et al., 2016). Moreover, as a result of resurgence over the last ca. 12 000 years, the central part of the CFc has undergone a long-term, antiformal uplift of ca. 100 m that is partly recorded by La Starza marine terrace's present-day elevation (ca. 40 m above sea level) that emerged ca. 5000 years ago (Di Vito et al., 1999; Sacchi et al., 2014).

The cause of ground uplift episodes and phases occurring at the CFc (magmatic vs. hydrothermal) is still debated and likely consists of periods of shallow magmatic intrusions accompanied by injections of deep fluids into shallow aquifers (e.g., De Vivo and Lima, 2006; De Natale et al., 2006; Lima et al., 2009; Moretti et al., 2018; Troise et al., 2019). Significant hydrothermal activity is shown on land and in the submerged portion of the caldera by the discharge of hot gases and liquids (Sacchi et al., 2014; Passaro et al., 2016; Chiodini et al., 2017; Steinmann et al., 2018). Since offshore emissions cover an area 4 times larger than the main onshore hydrothermal site around the Solfatara crater (Passaro et al., 2014; Somma et al., 2016; Steinmann et al., 2018), the marine portion of the CFc may play a substantial role in the recent dynamics of the caldera, representing an underestimated source of degassing and heat flux. The lack of adequate data on offshore fluid emissions prevents a correct estimate of the fluid release and gas and heat flow budget at Campi Flegrei. In addition, while the uppermost 100 m of the submerged part of the CFc have been intensively studied (D'Argenio et al., 2004; Milia and Torrente, 2007; Sacchi et al., 2009, 2014; Passaro et al., 2016; Steinmann et al., 2016, 2018), the deeper portion remains largely unknown.

Understanding the mechanisms for unrest and eruptions is of primary importance for confident hazard assessment. Data on the deeper, submerged portion of Campi Flegrei are required to constrain forecasts of the type, intensity, and frequency of future magmatic, phreatomagmatic, and hydrothermal eruptions. More than 600 000 people are potentially exposed to pyroclastic flows, rising to about 2 million considering the ash fall, also emitted from submerged vents (Rossano et al., 2004; Mastrolorenzo et al., 2006, 2008; Tonini et al., 2015; Sandri et al., 2016, 2018). Traditionally, calderas have been analyzed through field studies, monitoring observations, analogue models, and numerical simulations (e.g., Druitt and Sparks, 1984; De Natale et al., 1991, 2001, 2006; Martí et al., 1994, 2008; Gudmundsson et al., 1997; Gudmundsson, 1998; Burov and Guillou-Frottier, 1999; Acocella et al., 2000, 2001, 2004; Martí and Gudmundsson, 2000; Roche et al., 2000; Roche and Druitt, 2001; Folch and Martí, 2004; Lavallée et al., 2004; Geyer et al., 2006; Gregg et al., 2012, 2013). More recently, offshore reflection seismic imaging has emerged as a tool to understand the stratigraphic architecture and shallow structure of collapse-resurgent calderas in continental margins (e.g., Sacchi et al., 2009, 2014; Passaro et al., 2016; Steinmann et al., 2016, 2018). However, only deep drilling can provide conclusive information on the causes and mechanics of unrest and on the state and evolution of the magmatic–hydrothermal system. These data represent a fundamental prerequisite for evaluating the caldera-related hazards (Lowenstern et al., 2017).

2 Campi Flegrei caldera

Campi Flegrei is an active caldera belonging to the Neapolitan Volcanic District, which includes the active volcanoes of Vesuvius and Ischia Island. The caldera contains the westernmost districts of Naples as well as the towns of Pozzuoli, Bacoli, Baia, and Quarto and several smaller villages. Half of the CFc is submerged and forms Pozzuoli Bay (also known as the Gulf of Pozzuoli). This area has represented an active segment of the eastern Tyrrhenian margin since the Late Quaternary (Oldow et al., 1993; Ferranti et al., 1996) and may be considered a natural laboratory for studying the interplay between tectonics and explosive volcanism in the rifted backarc margin of the Tyrrhenian Sea and the Adriatic subduction system below the Apennine fold-and-thrust belt (Fig. 1) (e.g., Milia and Torrente, 1999; Acocella et al., 1999).

The CFc describes a quasi-circular depression approximately 13 km across. The present-day shape of the caldera has been conventionally interpreted as the result of two large collapses related to the eruptions of the Campanian Ignimbrite (CI, $\sim$ 39 ka; Giaccio et al., 2017) and the Neapolitan Yellow Tuff (NYT, $\sim$ 15 ka; Deino et al., 2004) (Fig. 2) with respective volumes of 200 km^3 DRE (dense-rock equivalent) (Rolandi et al., 2003) and 40 km^3 DRE (Scarpati et al., 1993). Evidence of older ignimbrites has been reported in the Campanian Plain (De Vivo et al., 2001) and in the distal marine archives (e.g., Insinga et al., 2014). The locations of these eruptions remain poorly constrained around Campi Flegrei. As described below, an alternative view now emerging is that the CI was erupted outside Campi Flegrei so that the caldera was formed only by the NYT eruption.

The CI eruption is Europe's largest explosive volcanic event recorded in the last 200 000 years. It has been considered a possible cause for the decline of the Neanderthals, thus implying a potential influence on human evolution (Fitzsimmons et al., 2013). The CI deposits are widespread in the Mediterranean, and its ash has been found in the Russian Plain, more than 2500 km away from the source (Pyle et al., 2006; Giaccio et al., 2008). The CI eruption was followed by the NYT eruption at 15 ka and at least 60 post-caldera eruptions (Di Vito et al., 1999). The most recent eruption occurred in 1538 after a repose of ca. 3000 years. It produced Monte Nuovo and was preceded by a century of uplift (Bellucci et al., 2006; Di Vito et al., 2016). Most recently, non-eruptive unrest episodes occurred during 1950–1952, 1969–1972, and 1982–1984 (Del Gaudio et al., 2010). They have been characterized by ground deformation (with rates up to 100 $cm\,yr^{-1}$), shallow, low magnitude earthquakes (about 16 000 events with a magnitude up to 4.0 in 1983–1984), and marked geochemical variations in the emitted gases (Berrino et al., 1984; De Natale and Zollo, 1986; Dvorak and Berrino, 1991; De Natale et al., 1991, 1995, 2001; Battaglia et al., 2006; Chiodini et al., 2015; Di Luccio et al., 2015; Moretti et al., 2017, 2018). In fact, the recorded history of non-eruptive ground movements goes back to Roman times as revealed by marine incrustations and mollusks on Roman and medieval buildings (e.g., Bellucci et al., 2006; Troise et al., 2019). Campi Flegrei thus represents the caldera with the longest record of ground movements not immediately followed by eruptions. Uplift began again in 2005 after 20 years of subsidence. It has been characterized by a slow movement of ca. 3 $cm\,yr^{-1}$ and less seismicity but a longer duration than previous uplifts (Troise et al., 2007; Chiodini et al., 2017; Moretti et al., 2018). The long duration of the ongoing unrest has led the Civil Protection Department to declare the first level on its alert scale (yellow), which implies an increase in monitoring activities.

Although the CI eruption has been previously considered as the main caldera-forming event (Rosi and Sbrana, 1987; Orsi et al., 1996), De Vivo et al. (2001) and Rolandi et al. (2003) presented evidence in favor of a fissure eruption to the north of the CFc. Recently, new evidence of buried CI products inside the caldera area at a depth of ca. 400 m beneath the surface has been found in the pilot borehole of the ICDP (International Continental Drilling Program) Campi Flegrei Deep Drilling Project (CFDDP) (De Natale et al., 2016). The shallow depth and modest thickness of the deposit (less than 200 m) raised further questions about a caldera collapse associated with the CI eruption. These and other studies highlight the complexity of the caldera system and, hence, the need for additional in situ information to fully understand the whole framework and evolution of volcanism in Campania. Due to its partly submerged setting, Campi Flegrei represents an ideal site to test the potential of IODP (International Ocean Discovery Program) shallow-water drilling on a volcanic continental margin by a multiplatform drilling pro-

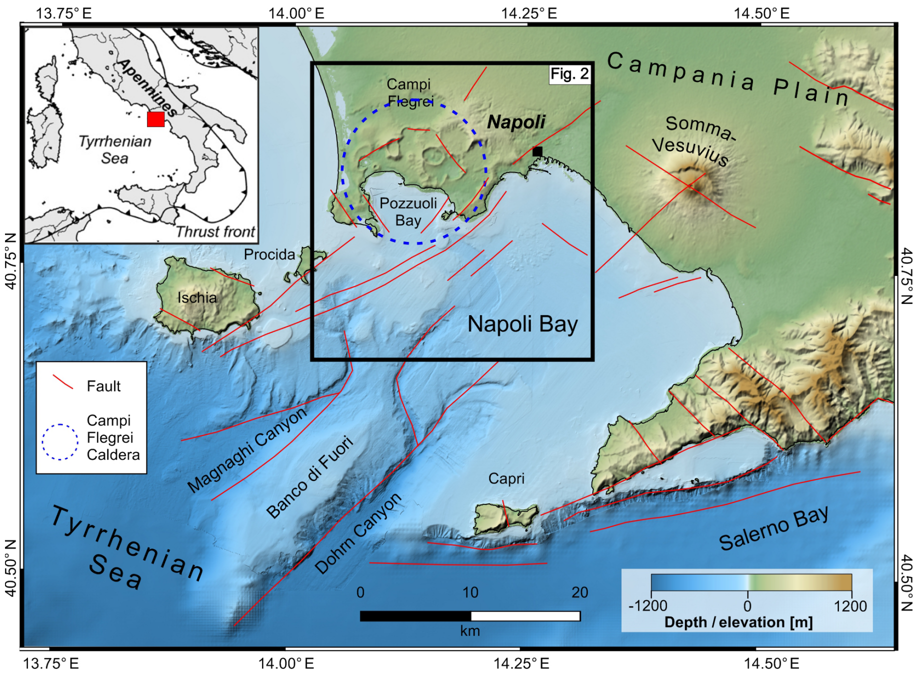

Figure 1. Tectonic sketch map of the Campanian continental margin in SW Italy with the location of the Campanian volcanic zone. Frame of Fig. 2 is also indicated.

gram including a land–sea transect, in the frame of a fully integrated IODP–ICDP Amphibious Drilling Proposal (ADP). The research outcomes derived from Campi Flegrei may also be transferred to similar partly submerged volcanic systems, including the Aira, Kikai, Krakatoa, Maug, Santorini, and Tavui calderas.

3 The MagellanPlus workshop

During the MagellanPlus workshop held in Naples on 25–28 February 2017, 35 participants from four European countries (Italy, Germany, Spain, and the UK), the USA, and Japan, gathered to discuss the key scientific issues for a coordinated IODP–ICDP proposal dedicated to drilling in the CFc. The workshop built upon previous research and networking activities, including (1) a coordinated ICDP and ESF (European Science Foundation) Magellan workshop held on 13–15 November 2006 in Naples; (2) an approved ICDP full proposal (Campi Flegrei Deep Drilling Project – CFDDP) in 2006–2008; (3) a submitted IODP pre-proposal (#671) in 2006–2007 with an indication of resubmission on the basis of an implemented site-survey package; (4) the realization of two pilot holes, a few meters apart, 500 and 200 m deep, as a preliminary phase to the ICDP deep drilling (the 200 m hole has been continuously cored by wireline drilling and used to install a borehole seismometer); and (5) the acquisition of new offshore site-survey data (3-D multiscale multichannel and single-channel reflection seismics, multibeam bathymetry, and gravity core data) between 2008 and 2016 (Fig. 3).

Participants at the MagellanPlus workshop represented a wide range of disciplines, including volcanology, geology, geophysics, geomorphology, petrology, geochemistry, and geochronology, as well as numerical and analogue modeling. The initiative was intended to bring together experts, early-career researchers, and other representatives from academia and industry involved in marine and continental research drilling. The aims were to (1) provide a global perspective on the potential and challenges of scientific drilling at active calderas, (2) discuss drilling issues on volcanic continental margin settings, (3) illustrate the new site-survey data, and (4) define drilling objectives for reconstructing stratigraphic events associated with the caldera's evolution and the interaction between magmatism and hydrothermal activity in coastal marine settings.

Participants were asked to contribute to scientific debates on volcanism and associated hazards over coastal areas and identify problems that can be addressed by coordinated marine and continental drillings, with reference to the CFc as a representative case study. The workshop program addressed data integration, the building of a scientific rationale for drilling strategies, and scientific partnering through a multidisciplinary approach, by linking geology, geophysics, volcanology, petrology, microbiology, and geotechnology. The event is among the first efforts to assess scientific themes directly related to volcanic hazards in highly populated coastal

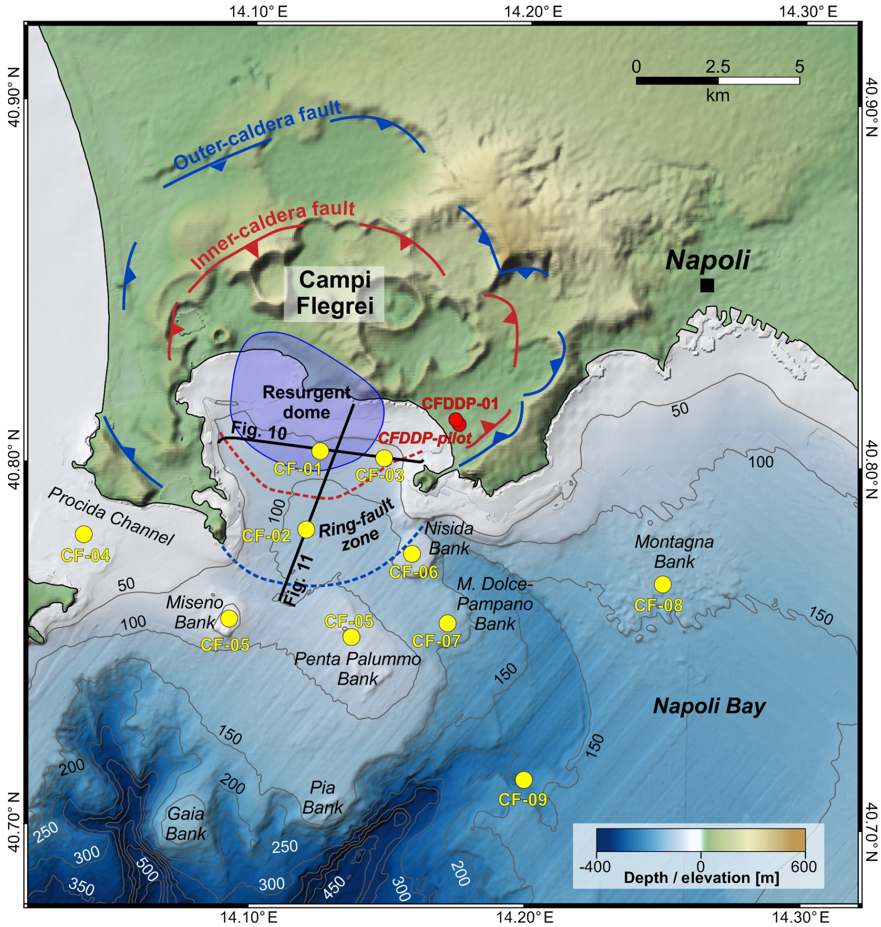

Figure 2. Digital Terrain Model (DTM) of the Campi Flegrei caldera (CFc) showing the structural border(s) and the offshore ring-fault–resurgent-dome system associated with the eruption of the Neapolitan Yellow Tuff (NYT) (∼ 15 ka), along with the most prominent subaerial and submerged volcanic morphologies of Napoli Bay. Location of seismic reflection profiles illustrated in Figs. 10 and 11 is also indicated.

areas within the context of fully integrated IODP–ICDP drilling research.

Fundamental questions were discussed on a wide range of topics, such as the mechanisms and timing of caldera formation and resurgence, ignimbrite deposition environments, magma transfer processes, and explosive volcanic activity in submarine and coastal settings, volcano-tectonic coupling, the dynamics and energy budget of onshore and offshore hydrothermal (geothermal) systems, subaerial vs. submarine volcanic unrest, and monitoring. Participants identified the following key questions and objectives that, which shall be addressed by the Amphibious Drilling Proposal:

- *Interaction between magmatic and hydrothermal processes*. This will be investigated regarding shallow crustal levels, the mechanism of submarine degassing and hot fluid discharge and their contribution to deformation, and recent unrest. What are the source, dynamics, and consequences of the hydrothermal activity in the marine portion of Campi Flegrei, and how are they related to unrest? Does the structural framework of the CFc exert control on the ascent of fluids and magma? Can microbial communities help in tracing hydrothermal fluid paths and defining thermodynamic environments and facies at depth?

- *Stratigraphy and structures of the CFc*. This will be investigated within the half-graben system of the Bay of Naples. This investigation includes recovering a representative stratigraphic record of the caldera fill and borders, down to the upper structural levels of the caldera floor and reconstructing the distribution of the CI (and older ignimbritic) deposits across the Bay.

- *Kinematic reconstruction of caldera collapse structure and resurgence*. This investigation includes reconstructing the pattern, timing, and rates of deformation involving the various structural components of the CFc system.

- *Eruptive history of the CFc*. When was the onset of volcanic activity, and what was the driving mechanism,

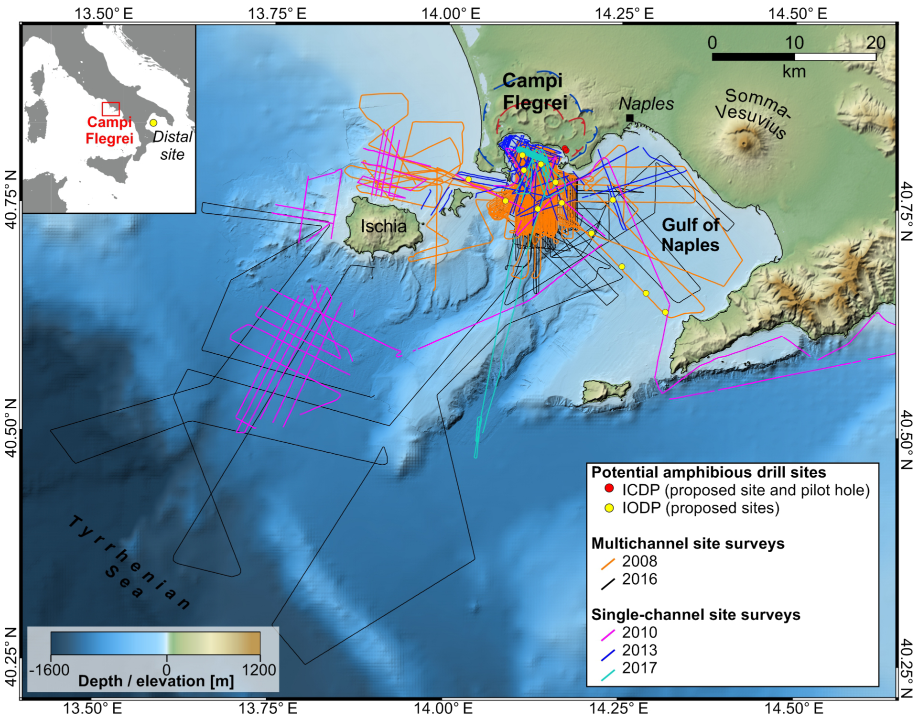

Figure 3. Offshore site-survey seismic data package (high-resolution multichannel and single-channel reflection seismic profiles) supporting the IODP component of the Campi Flegrei Amphibious Drilling Proposal. Locations of the proposed IODP drill sites and the ICDP site and pilot hole drilled in 2012 are also indicated.

e.g., volcano–earthquake interaction? In what way did the magmatic system change over time? Are there any major pre-CI ignimbrites originating from the Campanian Plain? What is the type of post-collapse, submarine volcanic activity? How have large eruptions changed the submarine morphology, and which are the syn- and post-eruptive deposition mechanisms?

- *Difference between terrestrial and shallow marine volcanism*. Why have post-collapse eruptions occurred preferentially in the onshore part of the caldera? Is the hydrothermal activity in the marine setting driving overpressure and fluid-saturated subvolcanic intrusions that are substantially different from on-land subvolcanic or volcanic processes?

- *Environmental and climatic impact*. This investigation refers to large-scale ignimbrite eruptions such as the CI and NYT events. Did these eruptions influence climate events? Did the CI eruption influence the decline of the Neanderthals? Do we recognize significant changes in the abundance and diversity of faunal and floral species after exceptionally large eruptions?

- *Establishment of an in situ monitoring systems*. This investigation regards the providing of optimal conditions for the quasi-real-time evaluation of critical parameters to be used as proxies to define the caldera dynamics.

4 Rationale of the Campi Flegrei drilling proposal

The outcomes of the workshop provided a conceptual framework for a full proposal for the drilling of the CFc to be submitted to the IODP and ICDP (Fig. 4) as an Amphibious Drilling Proposal. The Campi Flegrei ADP will combine complementary research topics into a general view on collapse-resurgent calderas located along continental margins. The partly submerged setting of the CFc provides a unique marine stratigraphic archive for a detailed reconstruction of the timing and kinematics of individual structures and components of the volcanic system, under different forcing factors (internal vs. external) during the past 10^6 years (Fig. 5).

The drilling is important to reconstruct the subsurface 3-D stratigraphic architecture, identify faults and volcanic or volcano-tectonic features, and obtain information on the hydrothermal discharge areas and thermal structure. It also provides valuable information concerning the eruptive history of volcanoes and the dynamics of eruptions with different intensity. Previous research in active volcanic areas has shown that drilling can be fundamental in clarifying and constraining structural interpretations based on geophysical data alone. For instance, drilling at the Kakkonda geothermal field in Japan revealed the steep permeability and lithological gradients where magmatic and hydrothermal regimes interact (Saito et al., 1997; Nakada, 2013). The IDDP-1 (Iceland

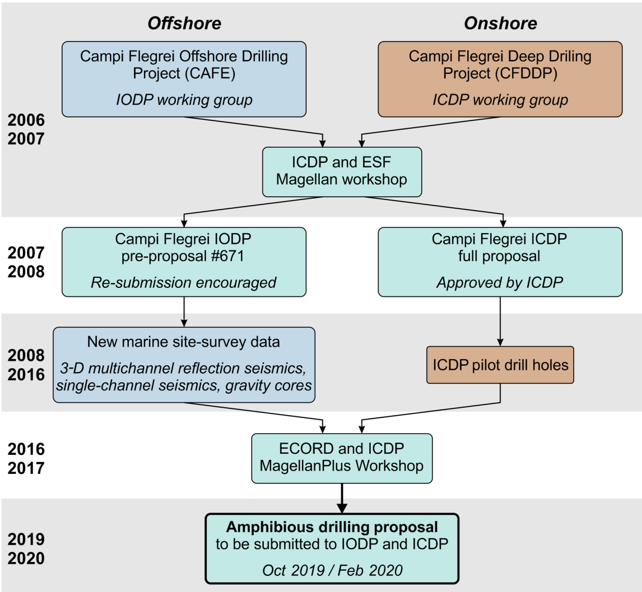

Figure 4. Flow chart illustrating the history of site-surveying activity and nurturing of the continental (ICDP) and marine (IODP) components of the Campi Flegrei Amphibious Drilling Proposal.

Timescales	Forcing	
	Internal	External
Active – historical - Unrest, restlessness - Eruptions	Fluids Hydrothermalism Magmatism (shallow / deep)	Sea-level change Tectonics
10^3 – 10^4 yrs - Post-caldera recovery, resurgence - Uplift, eruptions	Magmatism (shallow)	Sea-level change Tectonics Crustal detumescence
10^5 – 10^6 yrs - Volcanic-magmatic history - Cyclicity, periodicity	Magmatism (flare-up) Crust / mantle	(Sea-level change?) Tectonics

Figure 5. Timescales and forcing involved in the Campi Flegrei Amphibious Drilling Proposal (ADP).

Deep Drilling Project) well at Krafla in Iceland intercepted rhyolite melt in the region where geophysics had implied it would be absent (Elders et al., 2011). In the Long Valley Exploratory Well, a maximum temperature of $\sim 100\,°C$ was measured where the presence of shallow magma or at least very hot rock was assumed prior to drilling. Moreover, the use of selected drill holes as observatories provides an additional advantage for the in situ monitoring of volcanic and/or hydrothermal activity.

Drilling into active volcanic areas is not completely without risk, even though previous experiments in Japan and Iceland (Saito et al., 1997; Nakada, 2013; Elders et al., 2011) suggest that the chance of triggering a volcanic eruption is extremely small. The main risks are the hazards of possible underground pressure blowouts, meeting zones of fluid loss and material failure, and, more rarely, surface emission of liquefied sediments and steam (e.g., Sawolo et al., 2009). Documented experience indicates, however, that these risks can be significantly reduced or prevented by applying the appropriate mitigation techniques (e.g., blowout preventer systems) (e.g., Homuth et al., 2010).

4.1 Drilling at Campi Flegrei

The workshop was successful in identifying a number of relevant topics and questions, whose response may solve fundamental problems related to the caldera volcanism.

a. *The Campi Flegrei caldera represents an ideal example of an active caldera located in a shallow-water setting (< 200 m water depth).* Other ODP Legs (Ocean Drilling Program) (e.g., ODP Leg 157: Gran Canaria and Madeira Abyssal Plain) and IODP Expeditions (e.g., IODP Expedition 340: Lesser Antilles Volcanism and Landslides) have focused on volcanic islands in deep oceanic settings. Campi Flegrei provides a unique opportunity to obtain a high-resolution stratigraphic archive of explosive, effusive, and extrusive volcanism, volcano-tectonic dynamics, and unrest. Moreover, the proximal marine setting of the CFc documents the primary deposition and reworking of pyroclastic currents and fall deposits as components of the continental shelf slope system.

b. *Campi Flegrei is a primary site to unravel the timing, structure, and evolution of caldera resurgence and unrest based on the geological record of marine strata.* The mixed marine siliciclastic–volcaniclastic depositional architecture of the caldera fill provides a unique opportunity to document the pattern, timing, and rates of deformation related to resurgence since the Late Pleistocene. The last two millennia of documented unrest also provide further constraints in reconstructing time series of deformation onshore and offshore.

c. *The Campi Flegrei caldera generated the largest explosive eruptions in Europe during the Late Quaternary.* The results of drilling and well logging will have a high potential impact on paleoenvironmental–paleoclimatic reconstruction. The coupling of proximal drill sites off Pozzuoli Bay with the results from the drilling of the distal stratigraphic record will also help in reconstructing the dispersal and erosive patterns of co-ignimbritic tephras. Also, this record could provide some insights into the puzzling issue of the apparent causal relationships between the environmental effects of the CI eruption and the final decline of Neanderthals.

d. *Drilling off the shore of the Campi Flegrei caldera will help investigate the interaction between the magmatic and hydrothermal systems and the occurrence of a wide range of subaerial-to-submarine features from* *monogenic volcanoes to hydrothermal vents*. The apparent difference between the onshore and offshore evolution may be related to changing magma–water interactions under saturated conditions within the mixing zone between the phreatic and marine pore waters, and this can only be investigated in detail by an onshore–offshore drilling transect. Long-term borehole monitoring of physical, chemical, and microbiological parameters may additionally provide a chance to identify the potential precursors to eruptions for the purpose of risk mitigation.

4.2 Amphibious drilling

The half-submerged setting of the CFc provides an opportunity to integrate results from offshore and onshore drillings and available marine geology and volcanological data. A deep, onshore borehole (∼ 3 km) will allow the processes responsible for the recent unrest to be investigated at depth through the determination of rock physical properties, magma–water interaction, and water fluid chemical and physical exchanges. For instance, (1) extrapolated temperature measurements can be used to detect the depth of magmatic intrusions and the hydrothermal system; (2) the in situ chemical composition of fluids will provide information on rapid changes in the magmatic–hydrothermal system; and (3) deep monitoring systems will be deployed and incorporated in the existing network of the INGV-Napoli (Istituto Nazionale di Geofisica e Vulcanologia) (Osservatorio Vesuviano) to enable real-time tracking of such changes.

At the same time, a robust site-survey database, consisting of several multi-frequency (even 3-D) reflection seismic datasets (both single-channel and multichannel) has been acquired since 2008, yielding high-resolution images of the uppermost 100 m of the crust as well as new images to a depth of 1–2 km. Such a comprehensive database will enable a precise selection of offshore drill sites and guidance regarding deviated onshore drilling. The recent discovery of previously unknown volcanic structures and hydrothermal vents offshore offers a high potential for an integrated stratigraphic reconstruction (e.g., Sacchi et al., 2009, 2014; Passaro et al., 2016; Steinmann et al., 2016, 2018). The combined observations and data call for a joint offshore and onshore drilling program in order to (a) obtain an improved chronostratigraphic correlation between intra-caldera and extra-caldera products and (b) understand the origin of caldera collapse and the mechanisms of resurgence. An ideal drilling strategy at Campi Flegrei would therefore include the following onshore and offshore coordinated components:

a. *Onshore drilling and well logging down to a depth in the order of 3000 m to investigate the caldera deep structure and associated deep magmatic–hydrothermal system*. The drilling will provide the opportunity to investigate the processes responsible for the recent unrest episodes at depth, thereby allowing for a reliable evaluation of the hazard. This component includes (1) the acquisition of physical–chemical parameters of the geothermal system over the entire depth; (2) stress measurements (size and direction) at depth; (3) the permeability measurements at depth; (4) the extrapolation of temperatures in the supercritical layer to detect the depth of the magmatic temperature and locate magmatic intrusions; and (5) the determination of the physical, mechanical, and rheological parameters of deep rocks.

b. *Offshore drilling down to a maximum depth of ∼ 1000 m to investigate the shallow structural levels of the caldera fill and resurgence as well as to unravel the mechanisms of magma–water interaction as a function of depth*. This component provides the opportunity to study an undisturbed sedimentary archive without the challenges posed on land by intense subaerial erosion or urbanization (i.e., inaccessibility). This implies a much higher potential for structural, geochronological, petrographic, and geochemical reconstruction. Hence, marine drilling will provide a complete high-resolution stratigraphic record which will (1) improve the chronostratigraphy of volcanic and sedimentation events and unlock the timing and structural style of the deformation associated with inner-caldera resurgence, (2) understand the climatic effects and the environmental impact of ignimbrite eruptions on life and ecosystems, and (3) investigate the impact of magmatic–hydrothermal processes with respect to hydrothermal vents and shallow degassing structures as well as submarine monogenetic volcanoes and intrusions.

5 Drilling objectives and borehole logging and monitoring strategies

The workshop participants suggested that the IODP component of the ADP proposal should address the integrated stratigraphy of the caldera fill and resurgence, petrology, fluid geochemistry, and architecture of shallow structural levels (< 1000 m depth), whereas the ICDP component should focus on rock–fluid properties, physical–chemical processes, and the geothermal system at greater depth (< 3000 m). The proposed drilling strategy includes one major onshore drilling, complemented by an amphibious drilling transect extending from the Campi Flegrei shoreline towards the SE border of Naples Bay, together with distal drill sites in the Adriatic and Ionian Seas (Figs. 2, 6–12 and Table 1). Down-hole logging and long-term borehole monitoring at selected drill sites of primary physical and chemical parameters, along with microbiological analysis of rocks and fluids, within a depth range with a maximum of 0.5–1.0 km, have been also included in the planned operations.

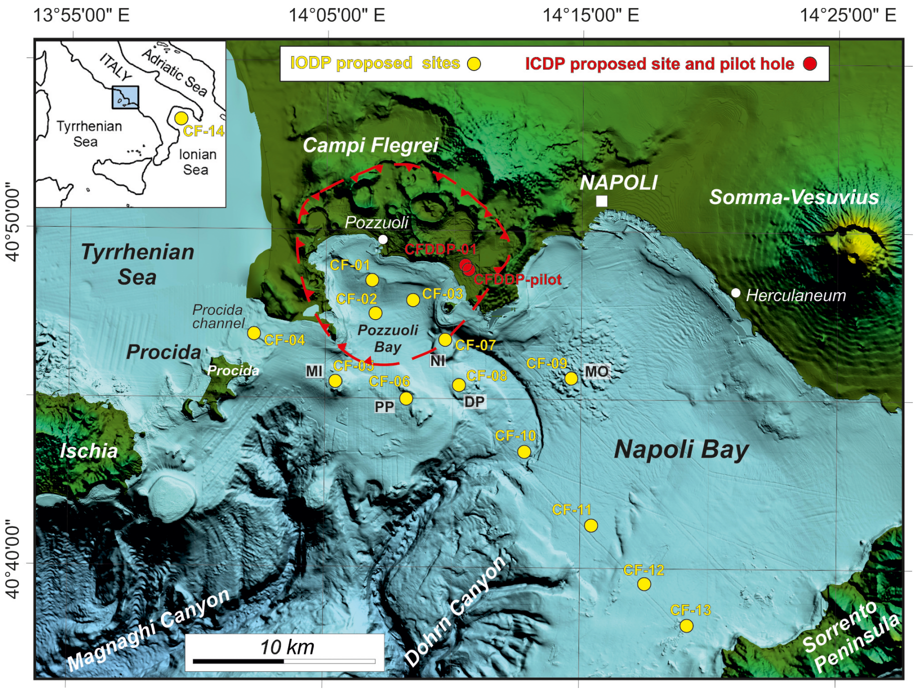

Figure 6. Location of onshore and offshore drill sites included in the first-draft plan of the Campi Flegrei Caldera Amphibious Drilling Proposal discussed during the MagellanPlus workshop.

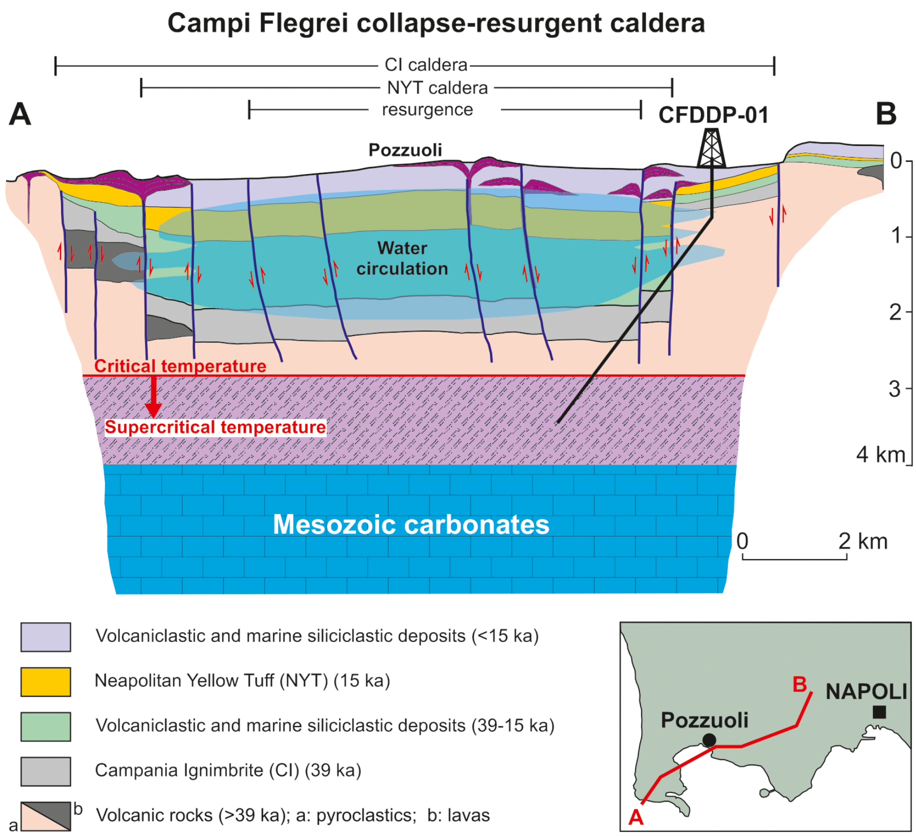

Figure 7. Illustrated section of the Campi Flegrei caldera structure indicating the targets of the proposed onshore (ICDP) drill site (CFDDP-01). The reconstruction is mostly based on geophysical and geological data, affected by large uncertainties. The depth limit critical water temperature is constrained by previous drillings in the area (AGIP, 1987). Modified after De Natale and Troise (2011).

Table 1. Summary of proposed onshore and offshore drill sites for the Campi Flegrei Caldera Amphibious Drilling Proposal (ADP).

ADP component	Proposed drill site	Structural sector	Drilling targets	Drilling depth (m)	Remarks
ICDP	CFDDP-01	Caldera margin	Stratigraphically reconstruct and well log through the hydrothermal system down to the brittle and ductile zone	∼ 3000	Deviated well, directed from the eastern border of the caldera towards the caldera center at depth
IODP	CF-01	Caldera center	Sample the stratigraphic succession of NYT caldera fill and penetrate the structural caldera floor	∼ 900	Deep offshore well within the caldera collapse area; maximum drilling depth to be agreed on with safety panels
IODP	CF-02	Flanks of the resurgent dome	Drill the post-15 ka caldera fill to reconstruct the timing of deformation and uplift of the caldera resurgence	∼ 50	Unique place to study the timing of the deformation of a caldera resurgent structure
IODP	CF-03	Caldera collar	Drill the subsurface magmatic intrusion and hydrothermal vent off the shore of Bagnoli (12–8 ka)	∼ 120	Subsurficial intrusion (6–4 ka); magma-water interaction; implications for volcanic hazard
IODP	CF-04	Caldera periphery	Drill the CI deposits in the shallow subseafloor of Procida Channel	∼ 100	Proximal facies of the CI
IODP	CF-05	Caldera periphery	Drill the stratigraphic succession of the peri-caldera monogenic volcano of Miseno Bank (> 120 ka)	∼ 80	Pre-caldera volcanism
IODP	CF-06	Caldera periphery	Drill the stratigraphic succession of the peri-caldera volcanic apparatus of Penta Palummo Bank (> 120 ka)	∼ 80	Pre-caldera volcanism
IODP	CF-07	Caldera structural border	Drill the stratigraphic succession of Nisida Bank (ca. 18–15 ka)	∼ 100	Caldera-related volcanism
IODP	CF-08	Caldera periphery	Drill the subsurficial intrusion and hydrothermal vent of Mt. Dolce–Pampano Bank (8–4 ka)	∼ 250	Subsurficial intrusion (18–15 ka); magma-water interaction; implications for volcanic hazard
IODP	CF-09	Caldera external periphery	Drill the volcaniclastic diapirs and mounds associated with hydrothermal venting at Montagna Bank (15–5 ka)	∼ 150	Soft-sediment deformation and volcaniclastic diapirism triggered by overpressured fluids
IODP	CF-010 CF-011 CF-012 CF-013	Proximal caldera exterior	Drill the Upper Quaternary mixed siliciclastic–volcaniclastic succession of Naples Bay for a stratigraphic purpose	∼ 200 ∼ 200 ∼ 200 ∼ 200	Drilling transect for the recovery of a composite stratigraphic section; proximal stratigraphic record of Campi Flegrei eruptions
IODP	CF-014	Distal caldera exterior	Sample distal products of major explosive events from Campi Flegrei and other eruptive centers of the Campanian district	∼ 100	Distal tephrostratigraphy

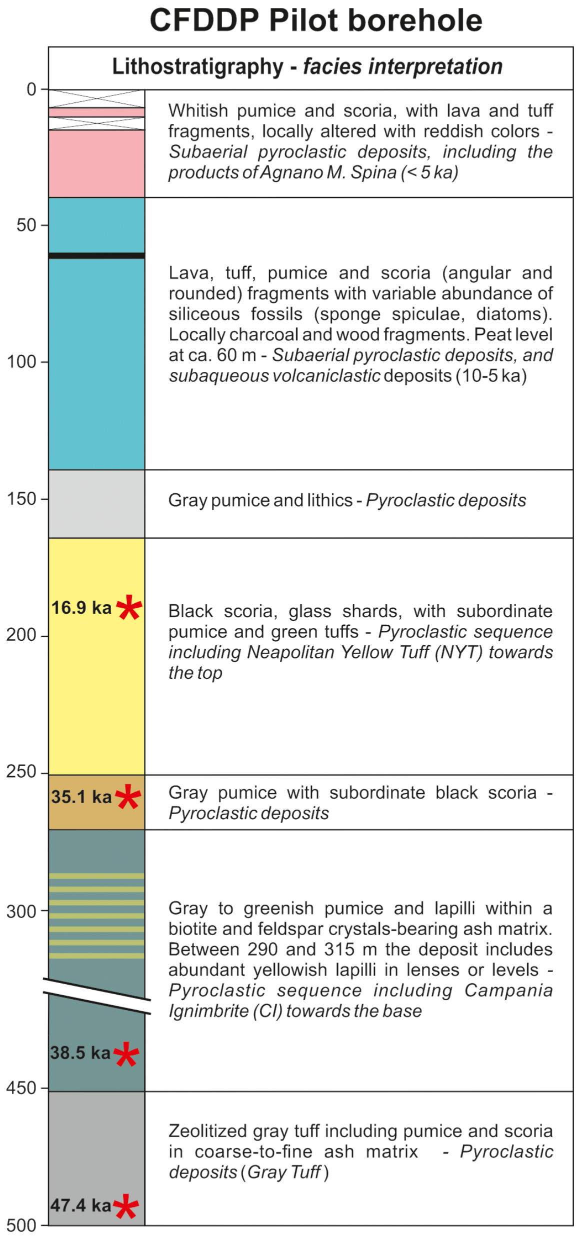

Figure 8. Synthetic lithostratigraphy and facies interpretation of the succession sampled at the CFDDP pilot borehole (500 m) on the shore of Bagnoli in 2012 (modified after De Natale et al., 2016). Red asterisks indicate the depth and $^{40}Ar/^{39}Ar$ age of sampled K feldspars. See Figs. 2–3 and 6 for the location of the borehole site.

5.1 Proposed on-land drill site (ICDP component)

Caldera margin to center

By drilling a ~ 3 km long deviated well from the eastern caldera margin towards its center (site CFDDP-01), we will be able to obtain a reference stratigraphic succession of the CFc fill to the basement floor and conduct well logging through the hydrothermal system down to the brittle and ductile zone (Figs. 2, 6–7 and Table 1).

Another important component of the on-land drilling will be the deployment of a network of in situ monitoring stations at depth to provide real-time insights into changes in the hydrothermal–volcanic system. Such information is crucial to understanding the ongoing unrest as well as to reliably assessing hazards and risks. The drilling of site CFDDP-01 will rely on the results of the 500 m deep pilot hole and associated well log data acquired by the INGV-Napoli in 2012 (Figs. 2, 6 and 8).

5.2 Proposed offshore drill sites (IODP component)

5.2.1 Caldera center – caldera fill, resurgent dome, and structural floor

The caldera fill represents a high-resolution archive of the post-caldera volcanic succession, as well as a record of the ground deformation caused by caldera resurgence. Hence, drilling the caldera fill will facilitate (1) the discovery of new insights regarding post-caldera volcanic history, (2) the reconstruction of the timing, duration, and conditions of caldera resurgence, and (3) understanding the caldera's subsurface structure. Penetrating the floor of the caldera (site CF-01) will provide conclusive information on the pre-caldera phase and caldera formation processes. Site CF-02 is designed to recover the stratigraphic succession that formed over the flanks of the resurgent structure, in order to provide ages and timing of volcano-tectonic deformation since the NYT caldera collapse (last 15 000 years) (Figs. 2, 6, 9–11 and Table 1).

5.2.2 Caldera collar – fractured, permeable zone

The annular depression ("collar") between the structural border of the NYT caldera and the inner-caldera resurgent dome is a highly fractured zone, characterized by ascending fluids and locally shallow magmatic intrusions. The area represents a remarkably permeable segment of the caldera structure and is a key location to study the interconnection between the deep magmatic–hydrothermal system and the surface and its role during caldera unrest. Site CF-03 is planned to drill through the shallow structural levels of the ring-fault zone of the NYT caldera collar down to small laccolith-like intrusion off the shore of Bagnoli (Figs. 2, 6, 9–10 and Table 1). Drilling operations will be limited to shallow depths (< 150 m) and will be only realized after stepwise monitoring of temperature and fluid pressure.

5.2.3 Caldera structural border – pre-NYT caldera vents and intrusions

The outer border of the CFc is characterized by a number of offshore vents, shallow magmatic intrusions, and ignimbrite

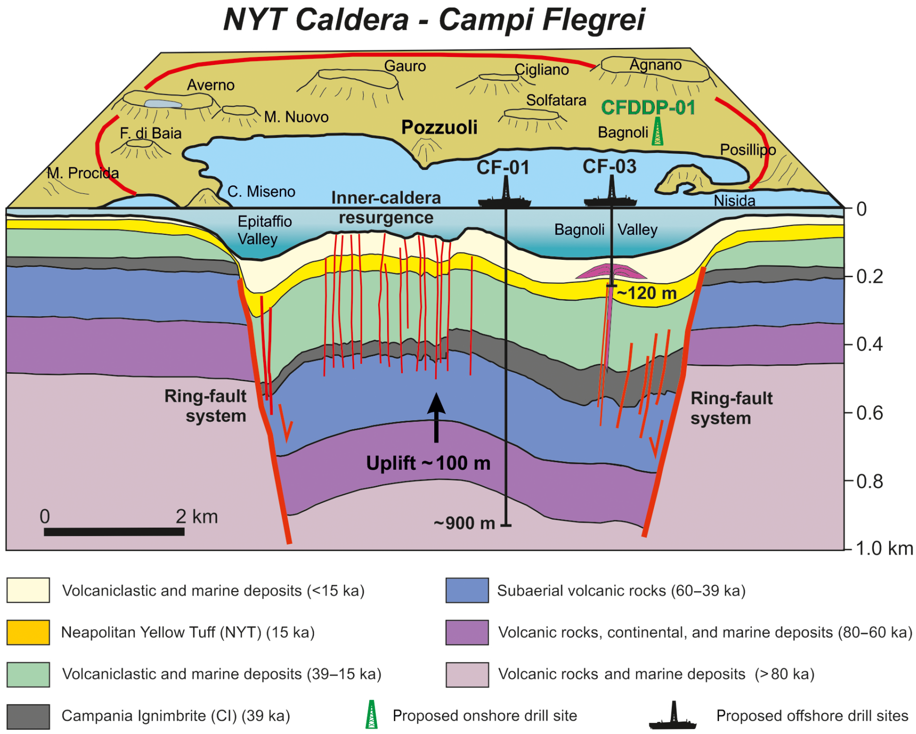

Figure 9. Schematic reconstruction of the shallow structure (< 1 km) of the collapse-resurgent caldera associated with the eruption of the Neapolitan Yellow Tuff (NYT) and the location of the proposed offshore (IODP) drill sites CF-01 and CF-03.

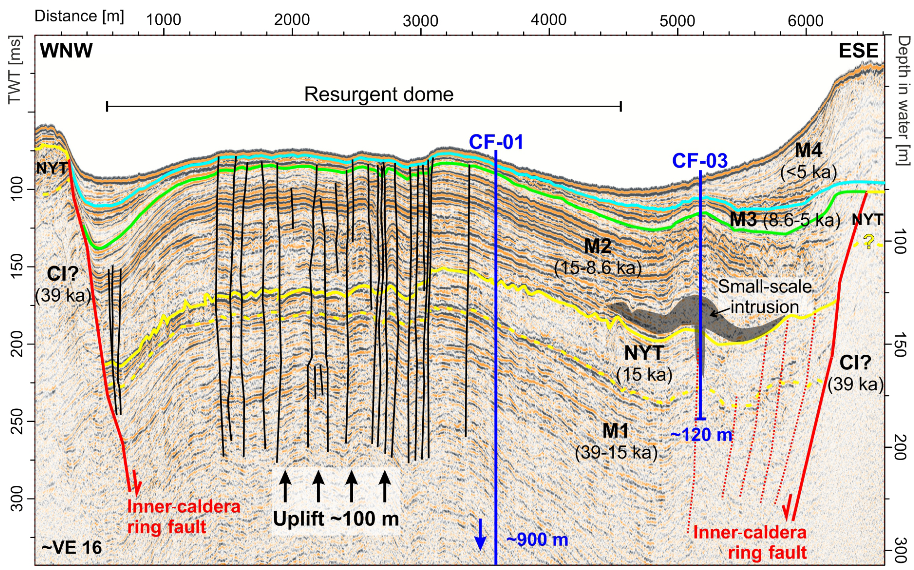

Figure 10. Interpreted high-resolution multichannel seismic profile across the CF caldera center and proposed location of drill sites CF-01 and CF-03. M1–M4 are the inner-caldera marine siliciclastic units; CI is Campanian Ignimbrite; NYT is Neapolitan Yellow Tuff.

deposits ranging in age from ∼ 120 to ∼ 18 ka. These provide a spectrum of volcanic features produced by significant magma–water interaction. They include most of the volcanic banks of the southern periphery of Pozzuoli Bay and CI ignimbrite deposits occurring at shallow depths beneath the seafloor, mostly between Procida and the mainland. Drill sites will aim to characterize the nature of these volcanic centers and units and their role in the onset of pre-CFc volcanism and the overall fluid circulation (as, for instance, Nisida Bank represents an active fluid vent). Drilling at site CF-04

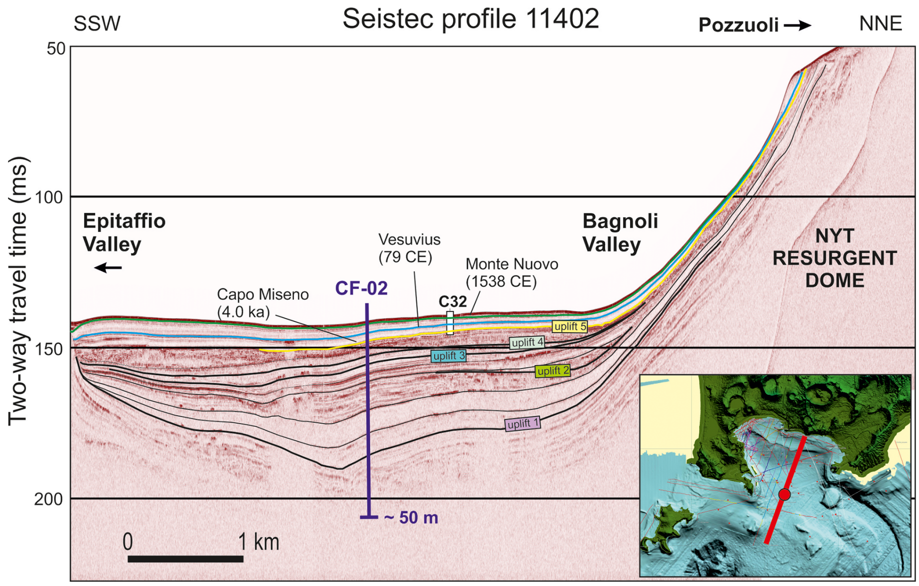

Figure 11. High-resolution single-channel seismic profile across the southern slope of the NYT resurgent dome and proposed location of drill site CF-02. Unconformities labeled as uplift 1–5 are interpreted as the result of a series of seafloor deformation phases associated with phases of the deformation of the resurgent structure. Correlation of tephra layers sampled by gravity core C32 is after Sacchi et al. (2014).

(Procida Channel) will focus on the recovery of a proximal succession of the CI. Drill sites CF-05 and CF-08 have been proposed to recover stratigraphic successions from a series of volcanic banks, namely at sites CF-04 (Miseno Bank), CF-05 (Penta Palummo Bank), CF-06, (Nisida Bank), and CF-07 (Mt. Dolce–Pampano Bank) (Figs. 2, 6 and Table 1).

5.2.4 Proximal extra-caldera area – Bay of Naples

Significant fluid venting in the Bay of Naples is not restricted to the ring-fault zone of the CFc, but it also occurs outside the structural border of the caldera itself. This is the case of Montagna Bank, a sub-circular seafloor region SE of Pozzuoli Bay that was formed by the dragging and rising up of volcaniclastic diapirs (consisting mostly of unconsolidated pumice), due to pore fluid overpressure at depth and associated fluid migration towards the seafloor (Passaro et al., 2016). Site CF-08 has been designed to drill through the volcaniclastic diapirs of Montagna Bank to the roots of the unconsolidated sediments involved in this process. The Naples Bay half-graben also represents an expanded, undisturbed sedimentary succession with interbedded massive ignimbrite deposits (NYT and CI). An offset drilling (CF-10 to CF-13) is an opportunity to cover a large time span of 1 million years (exceeding the entire time span of volcanic activity) with a transect of relatively shallow (~ 200 m) drillings (Figs. 2, 6 and Table 1). This will provide novel insights into the overall eruption history of the entire Campi Flegrei area and its tectonic evolution. Also, by drilling large ignimbrite units from top to bottom (i.e., contact zone of ignimbrite and siliciclastic units), their environmental impact and subsequent the recovery of life after major eruptions can be investigated.

5.2.5 Distal extra-caldera area – Ionian Sea

A distal drill site (CF-14) has been proposed to recover an undisturbed pyroclastic fallout archive allowing for an integrated tephrostratigraphic analysis of the entire eruptive history of the Campi Flegrei area and other eruptive centers in the Campanian region (Figs. 6 and 12).

5.3 Down-hole logging and borehole monitoring strategies

The well logging plan incorporates a wide spectrum of down-hole measurements which are designed to acquire maximum in situ information on petrophysical and geomechanical properties, as well as enhance monitoring of the strain–stress conditions, active seismicity, and the hydrothermal system at depth. The main parameters to be measured include (1) natural gamma rays, radioactivity, and spectrometry; (2) resistivity; (3) spontaneous potential redox; (4) sonic log; (5) magnetic susceptibility; (6) hole diameter (caliper); (7) temperature; (8) oriented microresistivity; and (9) acoustic and ultrasonic borehole images. The use of long-term borehole observatories (e.g., down-hole broadband seismic stations equipped with newly developed opto-electronic strain sensors and advanced monitoring systems that incorporate multiple seals allowing zoned measurements of in situ physical, chemical, and biological properties) may be considered for sites CFDDP-01 and CF-01.

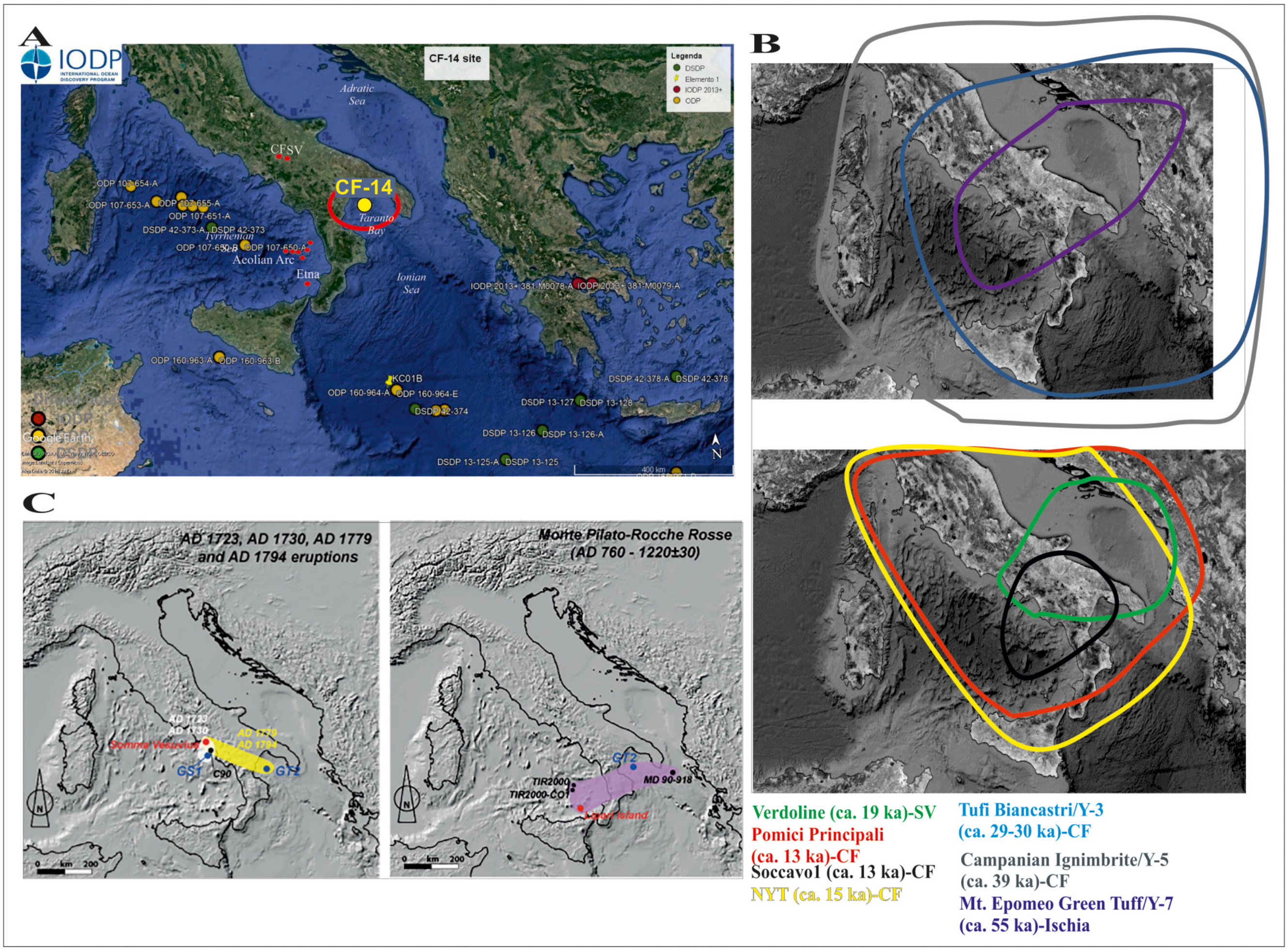

Figure 12. Proposed site CF-14 (Ionian Sea) for distal tephrostratigraphic reconstruction of Late Quaternary volcanism of the Campanian region (Crocitti et al., 2018; Di Donato et al., 2019). **(a)** Location map with an indication of the main DSDP (Deep Sea Drilling Project), ODP, and IODP archives (yellow for marine and green for terrestrial) of the central Mediterranean region; **(b)** dispersal maps of plinian and sub-plinian events (Bronk-Ramsey et al., 2015); **(c)** dispersal maps of moderately explosive eruptions (Sulpizio et al., 2014; Crocitti et al., 2018). Please note that the years given in AD in Fig. 12c correspond to those same years in the CE notation system.

6 Concluding remarks

Every eruption is preceded by unrest, but not every unrest culminates in an eruption (Acocella et al., 2015; Newhall and Dzurisin, 1988). Understanding the driving forces of volcanic unrest and the role of magmatic–hydrothermal processes is thus crucial for reliable hazard assessment. During the MagellanPlus workshop, all participants agreed that the CFc represents an ideal natural laboratory to study the interaction among volcanic, hydrothermal, marine, and volcano-tectonic processes. The amphibious Campi Flegrei drilling project, involving a deep ICDP and shallower IODP drillings, will address fundamental aspects including phreatic and hydromagmatic volcanism, caldera formation and subsequent structural resurgence and post-caldera volcanism, fallout and ignimbrite stratigraphy, hydrothermal-magma interactions, mechanisms of volcanic unrest, and volcano-tectonic coupling. The results will significantly advance our understanding of the most complex forms of volcanic structures on Earth.

Data availability. The onshore data supporting the work presented in this report are available at the INGV-Napoli (Giuseppe De Natale: giuseppe.denatale@ingv.it); offshore data are available at the Faculty of Geosciences of the University of Bremen (Volkhard Spiess: vspiess@uni-bremen.de) and CNR-ISMAR, Naples (Marco Sacchi: marco.sacchi@cnr.it).

Author contributions. MSa, GDN, VS, and LS jointly organized the workshop. MSa, GDN, LS, CK, and SDS drafted the paper. MSa, LS, and DI created the figures. All co-authors jointly contributed to the formulation of the concepts, scientific questions, and drilling/logging strategies discussed in the paper, according to their expertise: volcanology (SDS, NG, CS, HUS, MSu, and GV), petrology (LF), physical volcanology and volcanic hazards (GDN, VA, CK, AF, SP, RS, and CT), integrated stratigraphy (MSa, FM, and MV), structural geology of volcanic margins (VA, GV, and FP), tephrochronology (DI, PP, and ST), marine geophysics (VS, LS, SP, FP, and MC), and borehole logging (MJJ).

Competing interests. The authors declare that they have no conflict of interest.

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Scientific Drilling
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Workshop report on hard-rock drilling into mid-Cretaceous Pacific oceanic crust on the Hawaiian North Arch

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Abstract. The architecture, formation, and modification of oceanic plates are fundamental to our understanding of key geologic processes of the Earth. Geophysical surveys were conducted around a site near the Hawaiian Islands (northeastern Hawaiian North Arch region; Hawaiian North Arch hereafter), which is one of three potential sites for an International Ocean Discovery Program mantle drilling proposal for the Pacific plate that was submitted in 2012. The Hawaiian North Arch site is located in 78–81 Ma Cretaceous crust, which had an estimated full spreading rate of 7–8 cm yr^{-1}. This site fills a major gap in our understanding of oceanic crust. Previously drilling has been skewed to young or older crust (< 15 or > 110 Ma) and slow-spread crust. P-wave velocity structure in the uppermost mantle of the Hawaiian North Arch shows a strong azimuthal anisotropy, whereas Moho reflections below the basement are variable: strong and continuous, weak, diffuse, or unclear. We assume that the strength of the Moho reflection is related to the aging of the oceanic plate. The Hawaiian volcanic chain (200 km to the southwest of the proposed drill site) and the nearby North Arch magmatism on the proposed Hawaiian North Arch sites might also have affected recognition of the Moho via deformation and/or magma intrusion into the lower crust of the uppermost mantle. This workshop report describes scientific targets for 2 km deep-ocean drilling in the Hawaiian North Arch region in order to provide information about the lower crust from unrecovered age and spreading rate gaps from previous ocean drillings. Other scientific objectives to be achieved by drilling cores before reaching the target depth of the project are also described in this report.

1 Introduction

The architecture of oceanic plates is the fundamental question for understanding why plate tectonics has occurred on the present Earth. Subsequent to crustal accretion and prior to obduction, a broad array of processes leads to the modification of oceanic crust including tectonic overprint during ridge-to-trench seafloor spreading, chemical mass transfer and mineral modifications during low-temperature hydrothermal alteration and weathering, and biological activity. The nature of oceanic plates prior to subduction is key to describing and quantifying water and carbon fluxes into the deep Earth. The study of ophiolites, interpreted to represent obducted oceanic plate, has provided variable lines of information on the architecture of oceanic plates. However, the timing of mineralogical, chemical, physical, and biological processes during the aging of oceanic lithosphere exposed in ophiolites is often poorly constrained. Drilling is, therefore, still the only way to recover stratigraphically controlled samples of reasonable depth directly from the ocean floor.

Despite over 50 years of scientific ocean drilling, from the Deep Sea Drilling Project (DSDP, 1968–1983), the Ocean Drilling Program (ODP, 1985–2003), the Integrated Ocean Drilling Program (IODP, 2003–2013) to the International Ocean Discovery Program (IODP, 2013–present), only 18 holes have been drilled into more than 200 m of hard rocks of oceanic plates formed at the mid-ocean ridge (Michibayashi et al., 2019). Only one hole, Hole 1256D, was successfully drilled into the intact uppermost gabbro after the penetration of basalts and sheeted dikes (Wilson et al., 2006; Fig. 1).

Chikyu is the first riser drilling-equipped scientific research vessel, which is capable of drilling deep enough to reach the mantle. An IODP mantle drilling proposal for the Pacific plate was submitted in 2012 (Umino et al., 2013). The Pacific Moho to Mantle drilling project, abbreviated as M2M, is aimed at obtaining the most pristine material so that it can serve as a reference for the less-altered oceanic plate. Because the mantle drilling will produce the deepest hole in the ocean floor, we can also address many other fundamental and diverse questions such as the nature of the Moho, the construction of the lower crust, and the limits of life. Thus, the M2M helps understand the life of the oceanic plate in novel and exciting ways.

Sites for the mantle drilling were selected by both scientific requirements and by technological constraints. First, the temperature of the Moho at the site must be below 250 and 150 °C to safely drill and log, respectively. A location in a young hot plate is, therefore, not suitable for mantle drilling. Another major restriction is water depth, which should be shallower than circa 4000 m below sea level (m b.s.l. hereafter), because the anticipated maximum total length of the *Chikyu* riser system is 11 000 m (4000 m water depth + 7000 m penetration to the Moho in normal oceanic crust). Therefore, most of the oceanic plate in the Pacific Ocean is too deep for mantle drilling.

Considering these constraints, three candidate drill sites have been suggested: off the coast of Hawaii (off-Hawaii hereafter), off the coast of Mexico (off-Mexico hereafter), and the Cocos plate (Umino et al., 2013; Fig. 2). The Cocos plate region, which includes ODP Site 1256, is advantageous as the shallowest water depth among the candidate regions, but this crust is higher than the temperature at which logging tools can be used properly. At the off-Mexico site, 20 to 30 Ma crust is likely low in temperature at the depth of the Moho, but there are no reasonable seismic data sets to evaluate the characteristics of the Moho. The Hawaiian North Arch region is a unique site of lithospheric flexure surrounding the Hawaiian Islands (Bianco et al., 2005) that elevates the seafloor to shallow enough depths for access by *Chikyu*. The water depth in the northeastern Hawaiian North Arch (Hawaiian North Arch region hereafter) is around 4200 m (Ohira et al., 2018): ∼ 1500 m shallower compared with the average depth of 5500 m for a normal 80 Ma seafloor (McKenzie et al., 2005). Beyond the advantages and disadvantages of each site, we must obtain a clear seismic image of the Moho for the final site selection of the mantle drilling project. As shown below, a geophysical survey was conducted around the Hawaiian North Arch region, and new results on the diversity of the nature of the oceanic plate were reported (Ohira et al., 2018).

A workshop on developing a proposal for ocean drilling in the Hawaiian North Arch region was held in Kanazawa, Japan, on 6–7 November 2018. The goals of this workshop were (1) to share information about the Hawaiian North Arch region and other proposed hard-rock drilling sites that would use *Chikyu*, (2) to identify major scientific objectives for ocean drilling into the northeastern Hawaiian North Arch, and (3) to evaluate possible drilling sites; 37 researchers and students participated in this workshop.

2 The Hawaiian North Arch region

2.1 Recent geophysical survey results

In order to investigate the detailed seismic structure of the crust and the uppermost mantle at the off-Hawaii site, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the University of Hawai‘i conducted a 2-D marine seismic survey (an active-source refraction and reflection survey) in the central Pacific Ocean north of the Hawaiian Islands from August to November 2017 (Fig. 3). Multi-channel seismic (MCS) reflection data were acquired with a 444-channel, 6000 m long streamer cable with a 12.5 m interval between hydrophones, towed at a depth of 12 m. For the acquisition of the wide-angle seismic data, five ocean bottom seismographs (OBSs) were deployed by the R/V *Marcus G. Langseth* and recovered by the R/V *Kilo*

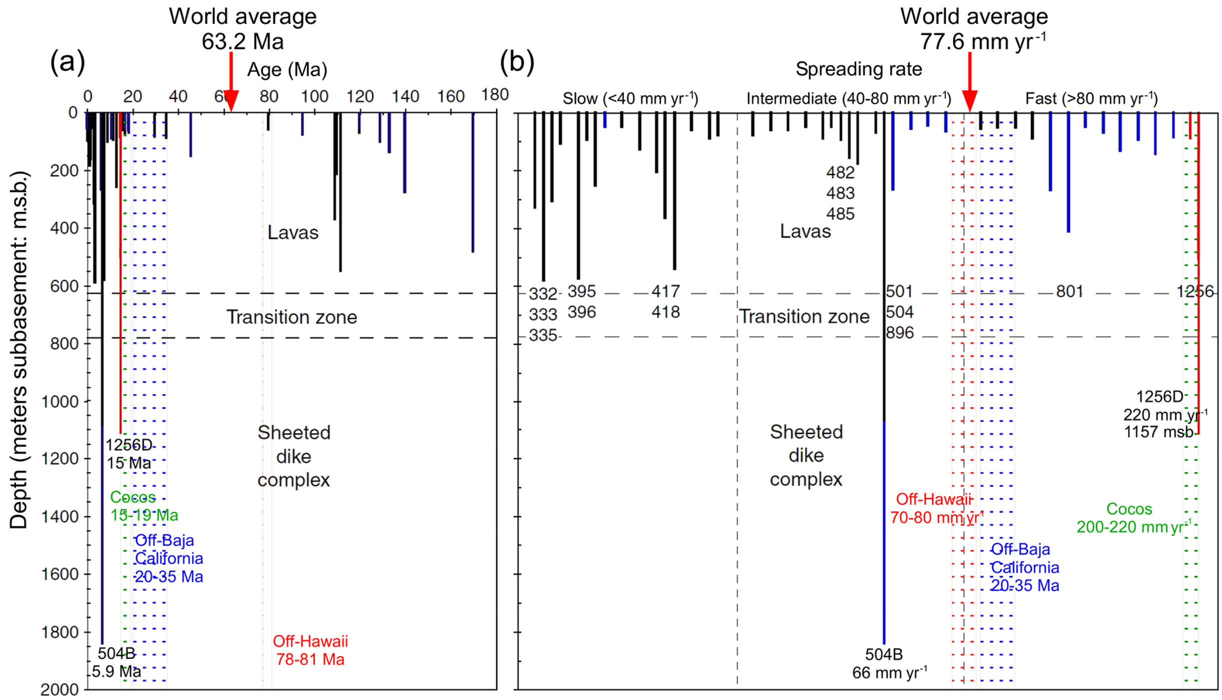

Figure 1. Ocean drill holes deeper than 50 m into the oceanic basement plotted against **(a)** the basement age and **(b)** categorized on the basis of spreading rate that formed the basement crust. World average age and spreading rate are based on the 3.6 min grid data from the Earth Byte age grid (Müller et al., 2008).

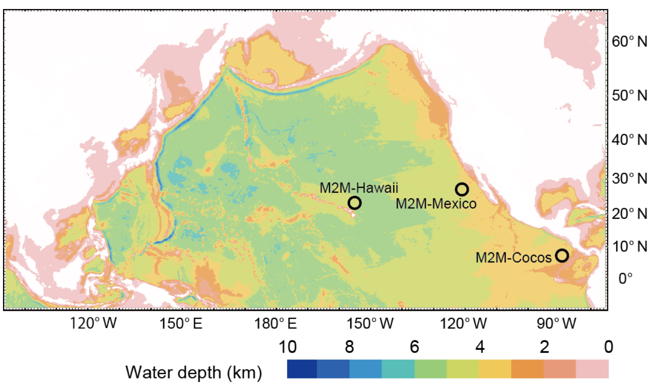

Figure 2. Bathymetric map of the Pacific Ocean showing candidate sites for the Moho to Mantle (M2M) drilling proposal.

Moana. Tuned airgun arrays (volume 7800 cubic inches) were fired by the R/V *Kairei* at intervals of 50 m along the EW, NS2, NS5 lines and at intervals of 50 and 200 m along the NS1 line. The total length of survey lines is 1150 km.

The preliminary results of MCS profiles and P-wave velocity structure using OBSs were reported by Ohira et al. (2018). Their results show typical oceanic crustal structure of oceanic crust from the Hawaiian Arch to the ocean basin. The P-wave velocity structure in the uppermost mantle shows strong azimuthal anisotropy. To image the detailed reflection structure, we applied the prestack migration technique using the initial velocity of the P-wave velocity structure by Ohira et al. (2018) for MCS data. The reflections from the Moho are characterized by images of a sharp, flat, continuous, and large amplitude (Fig. 4). The clear refraction phase from the boundary with an apparent velocity of more than 8 km s^{-1} is also observed in record sections of the OBSs (Ohira et al., 2018). Moho reflections from about every 2 s in two-way travel time below the basement are locally strong and continuous as expected for "normal" oceanic plate, whereas weak, diffuse, or no Moho reflections were observed in other parts of the seismic profile. The appearance of spatially variable Moho reflections is hereafter called Moho diversity. In order to recognize the spatial crustal characteristics for the drilling proposal, we focus on the 3-D image around the OBSs. Although the OBSs were sparsely arranged, many reflectors from the upper crust to the upper mantle are identified around the crossing point of survey lines (Figs. 5 and 6). It is important to obtain high-resolution velocity information in order to evaluate the Moho reflection for the drilling proposal.

2.2 Significance of drilling into the Pacific crust on the Hawaiian North Arch

Although seismic observations provide information of the architecture of the in situ oceanic crust, direct geological information of deeper portions of tectonically undisturbed normal oceanic crust can only be obtained by deep-ocean drilling. A

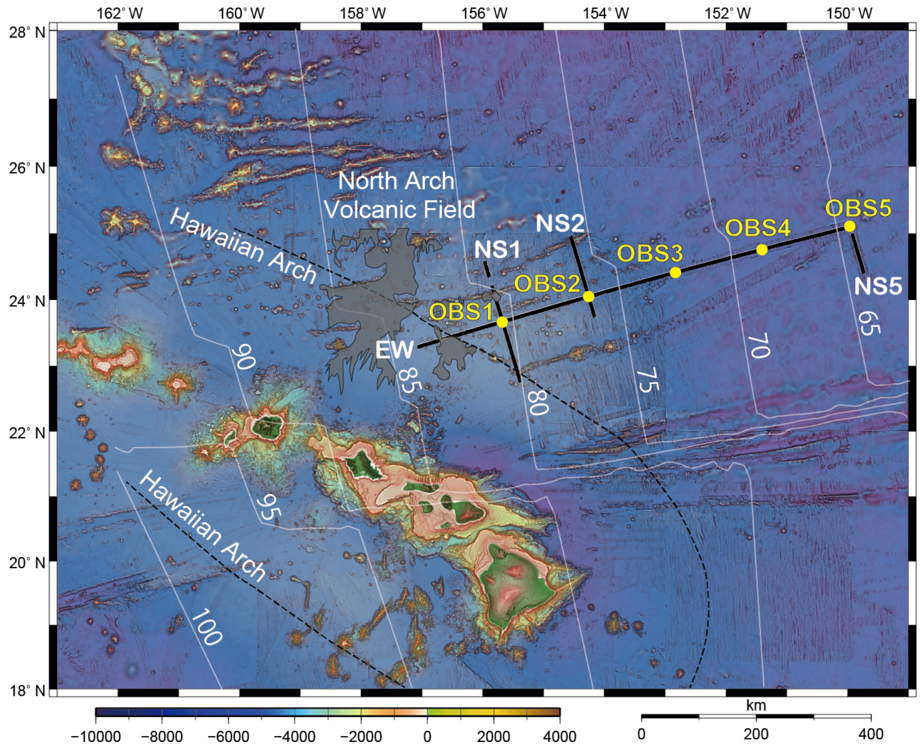

Figure 3. Map showing the seismic survey lines (black) northeast off the Hawaiian Islands. Yellow circles indicate the location of ocean bottom seismographs (OBSs). Thin white lines indicate seafloor age (Ma) from Müller et al. (2008). The black dashed line indicates the axis of the Hawaiian Arch (e.g., Ballmer et al., 2011; Holcomb and Robinson, 2004). The North Arch Volcanic Field, indicated by gray shading, is characterized by strong acoustic reflectivity (Clague et al., 1990, 2002; Normark et al., 1989).

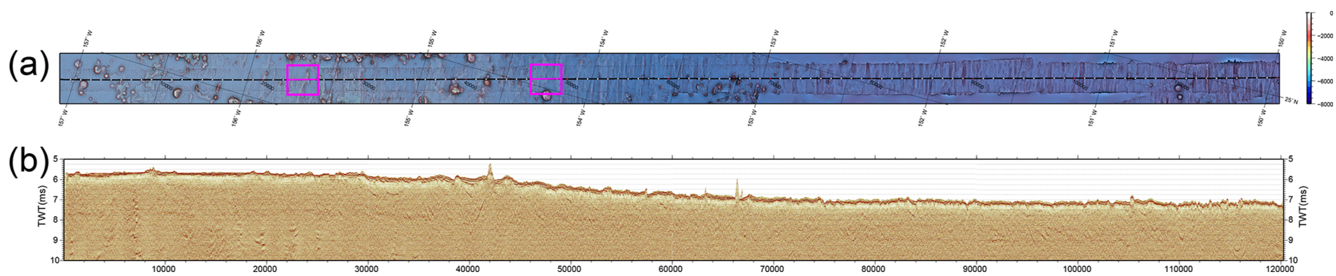

Figure 4. **(a)** Detailed bathymetry image along the EW line. Pink boxes show the location of Figs. 3 and 4. **(b)** Prestack time-migrated section of the EW line.

long-standing question is the nature of the seismic Layer 2–3 transition. Only Hole 504B penetrated through the Layer 2–3 transition within the sheeted dike complex, which appears to be controlled by alteration mineralogy or a change in porosity (Detrick et al., 1994; Alt et al., 1996). To test whether this Layer 2–3 transition is typical and true for crust spread at faster rates, Hole 1256D was aimed to drill into the 15 Ma crust, created by spreading at 22 cm yr^{-1}. Although the hole ultimately reached the gabbro below the sheeted dikes, seismic data suggest the Layer 2–3 transition has not been reached yet (Teagle et al., 2006). Besides these two, only limited numbers of holes have been drilled more than a few hundred meters into the basement of normal oceanic crust (Fig. 1; Michibayashi et al., 2019).

Oceanic drillings deeper than 50 m into mid-oceanic basement were skewed to young (< 15 Ma) or slow-spread crust (Fig. 1), with a wide gap of crust age between 20 and 110 Ma, including the world average age of 62.5 Ma and spreading rate of 7.6 cm yr^{-1} (Fig. 1). For example, deep basement drillings (Holes 504B and 1256D) were conducted in young crust (< 15 Ma). Among the three candidate sites of M2M, only the off-Hawaii site can provide information about oceanic crust within the gap regarding age and spreading rate. Deep drilling at the off-Hawaii site, penetrating through the upper crust and into the gabbros, will enhance our un-

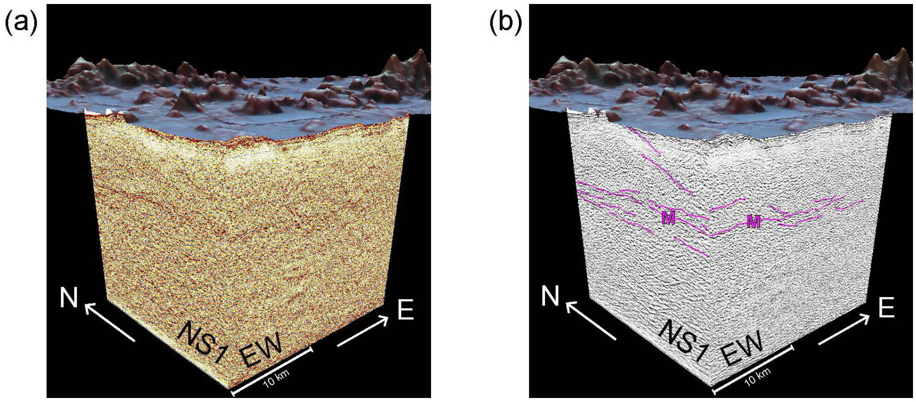

Figure 5. Three-dimensional view from the southwest to the northeast around the OBS1. **(a)** Prestack time-migrated section. **(b)** Reflector interpretation. M denotes the Moho reflection.

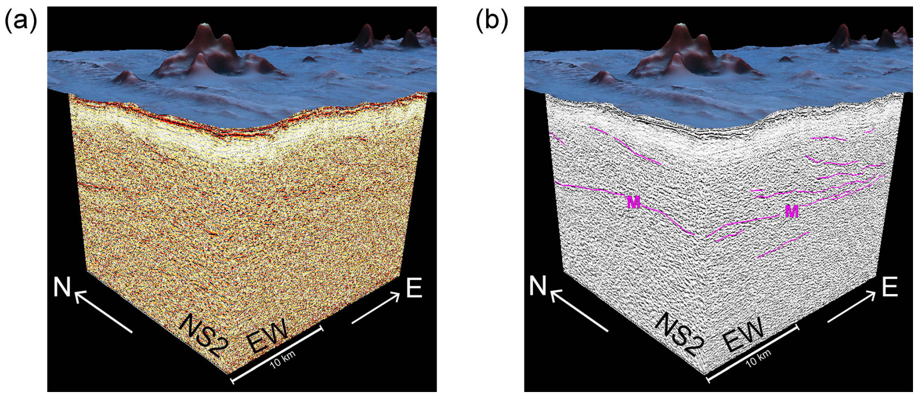

Figure 6. Three-dimensional view from the southwest to the northeast around the OBS2. **(a)** Prestack time-migrated section. **(b)** Reflector interpretation. M denotes the Moho reflection.

derstanding of the nature of the Layer 2–3 transition and the magmatic accretion and hydrothermal cooling at depth.

2.3 North Arch volcanism and its effects on modifications of the oceanic plate

The North Arch Volcanic Field covers $\sim 24\,000\,km^2$ of ocean floor (Fig. 3). The volume and age of North Arch volcanism is poorly constrained, but they are estimated to be $10^3\,km^3$ and 0.5–1.5 Ma (Clague et al., 2002). The calculated eruption rates are $\sim 1\,km^3\,kyr^{-1}$ corresponding with $\sim 1\,\%–2\,\%$ of the Kilauea eruption rate during peak times of eruption. The geochemistry of the lavas is highly alkaline basalts (Dixon and Clague, 2001). Due to the timing of eruptions, eruption rate, and chemistry, the North Arch volcanism is compared with the rejuvenated stage volcanic activity in the axial Hawaiian volcanic chain, which occurs after the shield until the post-shield stage (Garcia et al., 2010). Source mantle chemistry of the North Arch basalts is thought to connect them to the Hawaiian plume (Dixon and Clague, 2001; Garcia et al., 2010; Kimura et al., 2006). Estimated equilibrium melting pressure of the North Arch magmas corresponds with the lithosphere–asthenosphere boundary at 70–80 km (Li et al., 2004). Although the original seismic structure of the uppermost mantle is unaffected by the North Arch volcanism, crustal P-wave velocity (Vp) beneath the North Arch, which is slower than for the undeformed Pacific plate by 0.2–0.3 $km\,s^{-1}$, is ascribed to the presence of open cracks in the upper crust by extensional stress on the flexured North Arch lithosphere (Ohira et al., 2018).

3 Workshop outcomes

The unusually shallow seafloor allows *Chikyu* to access the lower oceanic crust and mantle in 80 Ma seafloor. Drilling the off-Hawaii region is appealing based on two important geological features: (1) to date no lower crustal materials from the 80 Ma Pacific plate have been sampled (Fig. 1), and (2) unusual Moho diversity is observed in the Pacific plate (Figs. 4, 5, and 6). The workshop briefly summarized the previous hard-rock drilling results and considered what should be addressed by a new drilling project in the Hawaiian North Arch regions. The target depth of the drilling should exceed the seismic Layer 2 and Layer 3 boundary, in order to acquire a complete section of intact lower crust from the 80 Ma Pacific plate. In order to understand the nature of the oceanic plate, it is essential to observe and describe the conditions for the boundary and transition between seismic Layer 2 and Layer 3 by drilling. We also discussed the scientific objectives that can be achieved by drilling cores before reaching the target depth of the project.

3.1 Lessons from previous drilling efforts

3.1.1 Formation of the oceanic crust

Seismic observations along the Galapagos Spreading Center (GSC) show thickening on-axis and thinning total extrusive rocks with axial magma chamber (AMC) depth, indicating that axial valleys, which are formed by dike intrusions and/or fault displacement, develop to trap thick on-axis flows with a deepening AMC and a decreasing magma supply rate (Fig. 7; Blacic et al., 2004). For the GSC spreading rate of 4.5–5.5 cm yr^{-1}, more than 50 % of flows in the axial valleys are pillows (Fig. 8; Ayadi et al., 1998; Bonatti and Harrison, 1988; Meyer and White, 2007; Tominaga et al., 2009; Tominaga and Umino, 2010; Susumu Umino, unpublished data, 2019). Consequently, the GSC is underlain by less dense pillows interbedded with fault breccias, which decreases the average density of the extrusive section with the development of an "apparent" level of neutral buoyancy (LNB; Rubin, 1990, 1995). The accumulated stress on the upper crust is relaxed by fault displacement in the uppermost extrusive rocks and by dike intrusions emplaced in the level of neutral buoyancy, which leads to the development of a rugged summit and axial troughs. This density structure of the upper crust is essentially the same as that of the ODP 504B crust (Dick et al., 1992; Fig. 9a).

In contrast, isostasy-dominated fast-spreading East Pacific Rise (EPR) extends solely by dike intrusions. Total extrusive thickness decreases with AMC depth, whereas on-axis flow thickness remains constant (Fig. 7; Hooft, 1996; Hooft et al., 1997). This indicates the absence of axial troughs even at a minimum magma budget, and the upper crust extends by dike intrusions without fault development. This is facilitated by the presence of dense extrusive rocks comprising more than 80 % sheet flows, considering the spreading rates of 11–14 cm yr^{-1} (Fig. 8). This crust architecture is primarily the same as that of the ODP 1256D crust. As is expected for the ultrafast spreading rate of 22 cm yr^{-1} at Site 1256D, the extrusive rocks are dominantly of massive and lobate sheet flows, which are as dense as the extruding magma (Teagle et al., 2006). This results in the upper crust being without an apparent LNB and the persistently over-pressurized axial magma chamber (Fig. 9b; Umino et al., 2008). Only a small increase in magmatic pressure or reduction in horizontal stress leads to dike intrusions followed by eruptions, and so the upper crust extends solely by dike intrusions.

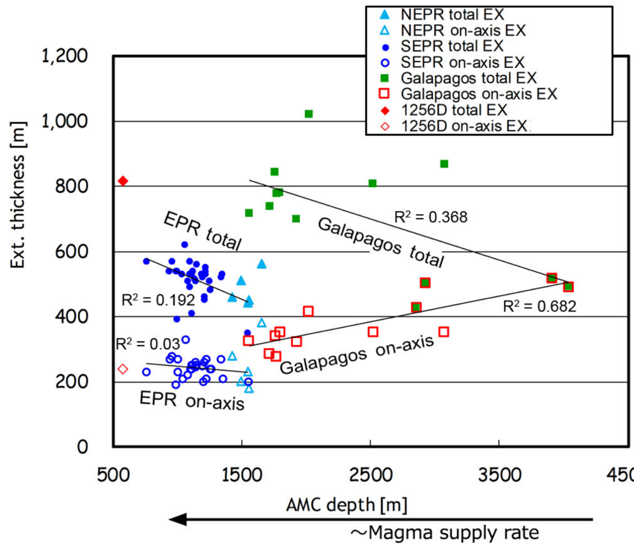

Figure 7. Extrusive thickness plotted against the AMC depth for the present Galapagos Spreading Center and the East Pacific Rise (EPR) segments and the 15 Ma 1256D crust. Solid and open symbols are data based on total and on-axis extrusive thicknesses. Data sources are Hooft et al. (1997; SEPR, NEPR), Blacic et al. (2004; GSC), Tominaga et al. (2009; Hole 1256D), and Tominaga and Umino (2010; Hole 1256D).

These observations suggest that magma-starved upper crust will have less dense extrusive layers than magma underlain by a thicker-sheeted dike complex, whereas a magmatically robust upper crust has dense extrusive layers comparable to the magma underlain by a thin-sheeted dike complex. These two types of upper-crust architecture result from the interplay of magmatic accretion and tectonic deformation, which determines the bulk density of extrusive layers and axial topography. Spreading rate dependency of axial flow morphology and ridge topography suggests that high-density crust is formed on the ridge axis spreading at > 10 cm yr^{-1} with sheet flows covering more than 70 % of the smooth ridge axes, whereas low-density crust is formed on the ridge axis spreading at < 7 cm yr^{-1} and is dominantly created by pillow flows with deeper axial troughs (Fig. 8). However, it is not clear whether the two types of upper-crust architecture gradually change from one type to the other or if there is any critical threshold that distinguishes two distinct types of upper crust. Upper crust created by spreading at an interval between 7 and 10 cm yr^{-1} is, therefore, key to understanding the governing factors of the upper-crust architecture. The Hawaiian North Arch site on the 78–81 Ma Cretaceous crust with an estimated full spreading rate of 7–8 cm yr^{-1} will provide a missing link that connects the two crust architectures and brings a more thorough understanding of seafloor spreading.

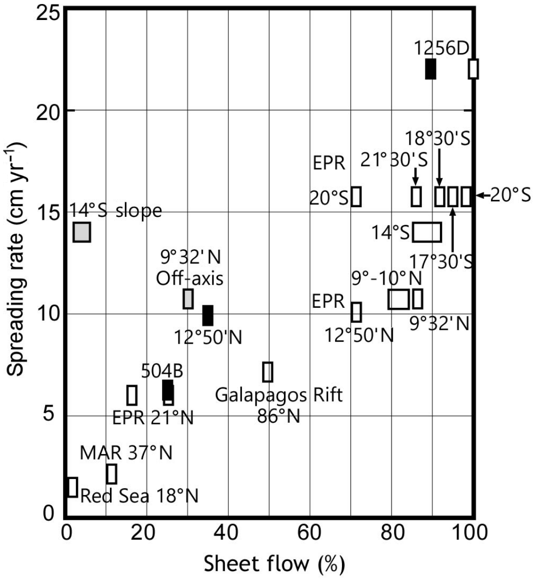

Figure 8. Spreading rate dependency of flow morphology of the mid-ocean ridges. Open, gray, and black symbols represent on-axis, ridge slope, and all data from on-axis to off-axis. Note that the spreading rate dependency of flow morphology stands only for on-axis flows. Even if the spreading rate exceeds $10\,\mathrm{cm\,yr^{-1}}$, steep ridge slopes are overwhelmingly covered with elongate pillows. This is because flow morphology of basalt lava extruded at a low rate is mainly determined by the basement slopes and changes from lobate lobes ($\sim 0°$) through elongate, flattened pahoehoe-like lobes ($< 7°$) to elongate pillows ($> 10°$; Umino et al., 2000, 2002). The data sources are Ayadi et al. (1998), Bonatti and Harrison (1988), Meyer and White (2007), Tominaga et al. (2009), and Susumu Umino, unpublished data, 2019.

3.1.2 Hydrothermal alteration of the oceanic crust

Hydrothermal circulation is a pivotal process in the transfer of heat and mass in ridge crest and ridge flank environments and provides the nutrients and energy for (sub-)seafloor life. Much of our knowledge about hydrothermal circulation is based on geophysical, mineralogical, chemical, and isotopic studies at or near spreading centers and ophiolites. In ophiolites, however, it is not always possible to differentiate between distinct hydrothermal events and processes prior to obduction. Except for two holes in the Pacific, 504B and 1256D, intact lower oceanic crust has not been sampled. The alteration patterns in both holes are broadly similar with low temperature phases in the volcanic section to (sub-)greenschist facies phases in the sheeted dikes (Teagle et al., 2006; Alt et al., 2010). The dike–gabbro transition, which was only sampled at 1256D, shows multistage alteration patterns from early amphibolite facies alteration and granulite facies overprint to subsequent alteration at (sub-)greenschist facies conditions (Alt et al., 2010; Harris et al., 2017).

While Holes 504B and 1256D have provided a wealth of information about hydrothermal processes in relatively young oceanic crust, it is evident from heat flow measurements that fluid percolation continues to $65 \pm 10\,\mathrm{Ma}$ (Stein and Stein, 1994). Heat transported by fluid flow in oceanic crust decreases with age, and it has been suggested that this is due to the clogging of pore space and decreased permeability (Stein and Stein, 1994). The volume of water circulating through ridge flanks and the aging oceanic crust (1–65 Ma) may be as high as $2 \times 10^{16}\,\mathrm{kg\,yr^{-1}}$, which is orders of magnitude higher than water circulation through ridge crest hydrothermal systems (e.g., Schultz and Elderfield, 1997). Beyond 65 Ma predicted and measured heat flow converge, but fluid–rock interaction may still continue. As a result, the oceanic basement rock may undergo prolonged oxidation (e.g., Klein et al., 2017), mineral dissolution, and precipitation, as well as chemical and isotopic changes, though it is largely isolated from the water column by sediments. While the dissolution and precipitation of minerals control porosity with important consequences for fluid flow, heat and mass transfer, and life (see below), we have been unable to assess these processes in aged intact oceanic crust due the lack of samples specifically from below the volcanic section.

3.2 Moho diversity in the Pacific plate

Aging of lithosphere is the cause of the diversity of the Moho in the Pacific plate (Ohira et al., 2018). The Moho reflection is weak in magma-starved segments and becomes obscured by deep crustal intrusions and by hydration and deformation of the lithosphere. Correlation of magma geochemistry, alteration, stress conditions, and seismic structures investigated by drilling enables us to understand the relationship between the Moho diversity and the aging of oceanic lithosphere, as well as by comparing these results with data for younger crust at Sites 504 and 1256 and older crust at Site 801.

P-wave velocity in the uppermost mantle obtained from the forward analyses in the seismic lines of Fig. 3 is 8.50–8.65 and 7.9–$8.0\,\mathrm{km\,s^{-1}}$ across and along the paleo-ridge direction, respectively (Fig. 9 of Ohira et al., 2018), which is common for the lithospheric upper mantle produced at fast-spreading ridges. This suggests that the uppermost mantle preserves its original structure formed at the ridge. The seismic cross section shows a reduction of crustal P-wave velocity from the un-deformed Pacific plate of $\sim 7.0\,\mathrm{km\,s^{-1}}$ to the deformed North Arch with a Vp of $\sim 6.7\,\mathrm{km\,s^{-1}}$ (Fig. 9 of Ohira et al., 2018). However, shallow faults found in the Layer 1 sediment do not differ much between the two areas. Further, the intra-crustal and Moho reflectors are considerably heterogeneous over these areas, and differences between the two areas are obscure (Ohira et al., 2018).

The North Arch magmatism also potentially modified the original architecture of the Pacific plate. The temperature of an 80 Ma oceanic crust is low (100–200 °C; McKenzie et

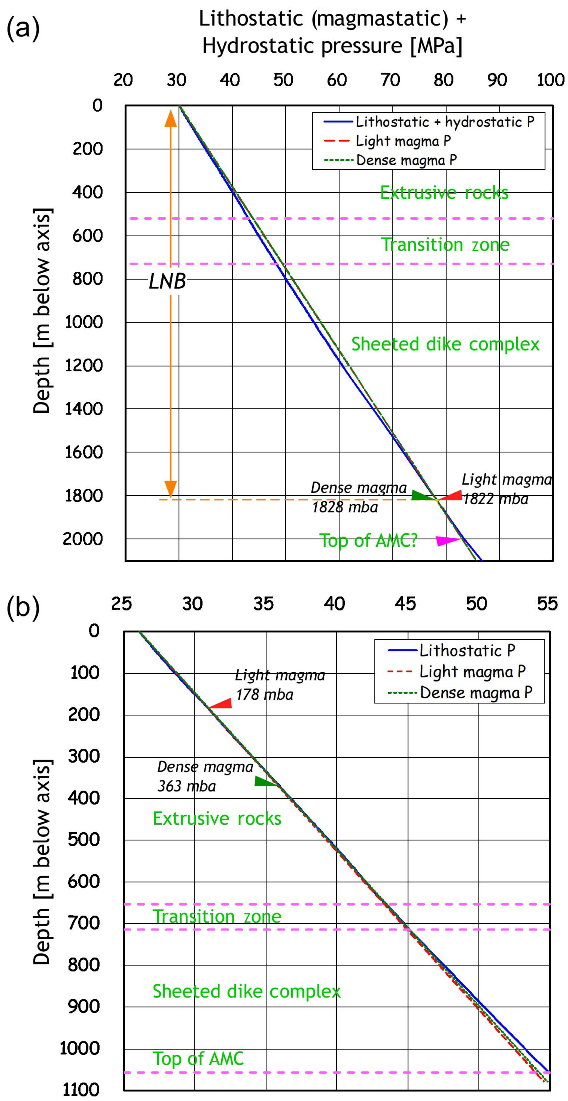

Figure 9. Estimated lithostatic–magmastatic pressure variations for Sites **(a)** 504B and **(b)** 1256D when they were at the ridge axis. **(a)** Using the lithodensity logs obtained during Leg 111, density structures of the upper crust were estimated by integrating all density data $> 2000\,\mathrm{kg\,m^{-3}}$ with depth, assuming water depth at the ridge axis of 3000 m, identical to that of the present Costa Rica Rift. The uppermost 50 m thick flows were emplaced out of the neovolcanic zone (Ayadi et al., 1998), and so they were eliminated from the lithostatic pressure estimate. Hole 504B lavas and dikes are nearly aphyric, relatively primitive (Mg# $(100 \times \mathrm{Mg}/[\mathrm{Mg}+\mathrm{Fe}])$ 68 %–56 %, MgO 8 %–9.5 %, FeO* (total Fe as FeO) 8 %–10.5 %), and are among the most depleted end-members of NMORB (Dick et al., 1992; Umino, 2003). Magma density was estimated using the program adiabat_1ph (Smith and Asimow, 2005) run in MELTS (Ghiorso and Sack, 1995) mode for representative primitive and differentiated compositions at an appropriate AMC depth up to the surface and at liquidus temperatures. The lower crust gabbro is presumed to be close to the bottom of the hole at 1526 m below seafloor; however, it is yet to be reached. Consequently, the AMC beneath the ridge axis is assumed to be at 1060 m in depth. Oxygen fugacity was assumed to be 2 log10 units below the quartz–fayalite–magnetite buffer (Christie et al., 1986). **(b)** Hole 1256D was penetrated through a 15 Ma ultrafast-spread ($22\,\mathrm{cm\,yr^{-1}}$) crust formed at the East Pacific Rise. Assuming the water depth at ridge axis of 2600 m, the densities of magmas at the AMC pressures of 53.7 MPa are estimated as 2698 and $2703\,\mathrm{kg\,m^{-3}}$ for primitive (FeO* 8.39 %) and differentiated (FeO* 10.2 wt %) magmas, respectively. Please refer to Umino et al. (2008) for more detail.

al., 2005). Therefore, the magma chambers that developed in such cold oceanic crust are unlikely to be long-lived tholeiitic shallow systems like Kilauea (Poland et al., 2014), but rather, they are likely deep-seated chambers near the lithosphere–asthenosphere boundary, as estimated by the post-shield alkali basalts (Kimura et al., 2006). Basalt feeder dikes are likely present within the Layer 3 gabbro. Such alkali basalt dikes appear to provide little thermal and chemical overprints of the surrounding crust. All those assumptions can be tested by drilling because of the contrasting compositions of the

$\sim$ 80 Myr old mid-ocean ridge-type Pacific plate basalts and the $\sim$ 0.5–1.5 Myr old alkaline North Arch basalts.

3.3 Deep biosphere in relatively old oceanic crust

The relatively old oceanic plate results in temperatures of < 150 °C even at the Moho depths, which is close to the upper temperature limit of life. Thus, the potential drilling sites are intriguing targets for studying a deep subseafloor biosphere in aged, hydrothermally overprinted igneous rocks of the lower crust.

In contrast to sedimentary rocks, crystalline igneous rocks are generally low in organic carbon and porosity, thus providing extremely low nutrient and energy supplies. However, microorganisms are possibly transported and migrate to fractures and interconnected pores. Compared to sedimentary rocks, the habitability of igneous rocks and their altered equivalents in the lower oceanic crust remain poorly understood and limited to slow-spreading ridges (Mason et al., 2010). Exploration of the deep subseafloor biosphere from the lower crust of intermediate-to-fast-spreading oceanic plates will provide a unique opportunity to investigate the diversity and survival strategies of microbial ecosystems in rocks that make up the majority of the Pacific seafloor.

3.4 Nature of the North Arch volcano

No primitive basalt was found from the North Arch area, suggesting either primitive basalts are undiscovered beneath sedimentary cover or efficiently differentiated (Dixon and Clague, 2001; Garcia et al., 2010). The presence of cracks in the upper crust on the flexured North Arch lithosphere reduces the bulk density of the upper crust, leading to the presence of apparent LNB in the mid-crust, where magma is trapped, fractionates crystals, and interacts with the wall rocks. Fundamental issues are if there is any primitive basalt hidden beneath differentiated lavas on the surface, how any mid-crustal magma chambers formed associated with the flexure, and to what extent and how the lithosphere is geochemically altered and structurally disturbed by the North Arch volcanism. Assimilation of Layer 2–3 (basalt–gabbro) characteristics by the North Arch basalts can also be explored by geochemical signatures, such as lower O, Sr, and Pb isotopes. Those can also be tested by drilling to recover more primitive North Arch basalt samples.

3.5 Giant Hawaiian landslides: frequency, size, and mechanics

The enormous size (up to 8.5 km of relief and 80 000 km^3) and rapid growth ($\sim$ 1 to 1.5 Myr) of Hawaiian volcanoes causes them to become gravitationally unstable and collapse (Moore et al., 1989). These collapses have generated some of the largest landslides on Earth, and they have undoubtedly produced colossal tsunami (e.g., Satake et al., 2002). Dozens of giant landslides, some with deposits extending more than 200 km from their source and with volumes > 1000 km^3, have been recognized along the Hawaiian Ridge (Moore et al., 1994). Considering only the deposits exposed on the ocean floor, the Hawaiian Ridge has major landslides every 32 km along its length. This suggests that a major landslide has occurred about every 350 kyr (Moore et al., 1994). However, drilling at ODP Site 1223 revealed that Koʻolau Volcano, a moderately sized Hawaiian volcano, produced at least four major and three other slides during a period of $\sim$ 0.7 Myr, and many more potential landslide deposits appear to be buried at depth (Garcia et al., 2006). Thus, existing data argue that large landslides are a common occurrence (once in $\sim$ 100 kyr) and are an important geologic hazard that requires additional investigation to assess their impact on the circum-Pacific regions. Drilling at the proposed site north of the main Hawaiian Islands will allow the frequency, size, and possible failure mechanics of such landslides to be better understood.

4 Summary

The diversity of the nature of the oceanic plate was reported by a geophysical survey around the Hawaiian North Arch region, which is one of three candidate drill sites of the Pacific Moho to Mantle drilling project. We summarize the scientific rationale of a workshop on developing a proposal for ocean drilling in the Hawaiian Arch region located in 78–81 Ma Cretaceous crust with an estimated full spreading rate of 7–8 cm yr^{-1}. The main objective of the drilling proposal is to understand the architecture and evolution of the oceanic crust and the relationship between the diversity of the Moho and aging of oceanic lithosphere. Previous drilling into tectonically undisturbed oceanic crust was limited and skewed to young (< 15 Ma) and slow (< 4 cm yr^{-1}) spreading rates. This leaves a substantial gap in our knowledge about crust age between 20 and 110 Ma, including the world average age of 63 Ma and spreading rate of 8 cm yr^{-1}. The Hawaiian North Arch site, with a spreading rate of 7–10 cm yr^{-1}, will enhance our understanding of the transition between slow-spreading ridges, which are dominated by extension, and fast-spreading ridges, which dominated by magmatism. The drilling into the Hawaiian North Arch region can also address other scientific objectives such as investigating a deep biosphere in relatively old oceanic crust, the North Arch magmatism, and giant Hawaiian landslides.

5 Participants of the hard-rock drilling workshop in Kanazawa, Japan

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Data availability. No data sets were used in this article.

Author contributions. TM, SU, SO, and KM organized this workshop in Kanazawa, Japan. SU and JK contributed North Arch volcanism data, MY contributed geophysical site survey data, MT interpreted the logging data, FK contributed data regarding hydrothermal alteration of the oceanic crust and the deep biosphere, and MG contributed data regarding North Arch volcanism and giant Hawaiian landslides. TM took the lead in writing the initial draft of the manuscript. All authors contributed improvements to the final paper.

Competing interests. The authors declare that they have no conflict of interest.

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Scientific Drilling
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The Bouse Formation, a controversial Neogene archive of the evolving Colorado River: a scientific drilling workshop report (28 February–3 March 2019 – BlueWater Resort & Casino, Parker, AZ, USA)

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Abstract. Neogene deposits of the lower Colorado River valley, especially the Miocene(?) and early Pliocene Bouse Formation, have been the focus of intense debate regarding the early paleoenvironmental history of this important continental-scale river system in southwestern North America and its integration with the proto-Gulf of California. Fine-grained units within these Neogene deposits also hold a promising archive of Pliocene paleoclimate history for this part of the world. Because the depocenter deposits of the Bouse Formation and the deposits that overlie and underlie it are poorly exposed and highly weathered, the formation is ripe for study through collection of drill cores. A workshop was held 28 February–3 March 2019 in Parker, AZ, USA, to discuss how scientific drilling might be employed to help resolve the Bouse controversies and improve our understanding of paleoclimate history in the region.

1 Introduction

The Colorado River (CR) is one of the longest rivers of North America (2330 km), with a watershed spanning 640 000 km^2 of eight US and Mexican states, making it a critical resource for the arid southwestern part of the continent. This dynamic modern river is imperiled today by overutilization of its water resource and a changing climate. Just as the river system today presents a rapidly unfolding story of environmental change, its past geological history along with the basins receiving its water and sediment present scientists with critical lessons for understanding possible future change.

A key archive of this past history can be found in the late Miocene(?) and early Pliocene Bouse Formation, which crops out and is present in the subsurface along the lower CR valley of western Arizona, southern Nevada, and southeastern California today (Figs. 1, 2) (Metzger, 1968; Buising, 1990; House et al., 2008). The Bouse Formation, which can range from less than 10 m thick in some outcrop exposures to over 250 m in subsurface wells, contains the depositional record of a number of large water bodies, and the scientific investigation of this unit has a legacy of controversy that continues to today. The largest of these water bodies, which occupied the Blythe basin and adjacent areas, covered over 10 000 km^2 (Spencer et al., 2013), almost twice the size

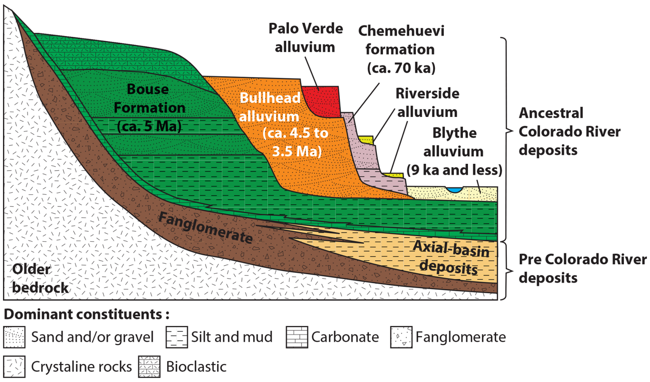

Figure 1. Simplified stratigraphic and geomorphic relationships of Neogene formations exposed in the lower Colorado River basin (after Buising, 1990; Howard et al., 2015; Crow et al., 2019a). Ages for the Palo Verde alluvium (Late Pleistocene; Lundstrom et al., 2008) and the Riverside alluvium (Early(?) or Middle Pleistocene; House et al., 2018) are poorly constrained.

of the modern Great Salt Lake (Utah). For decades, geologists, paleontologists, and geochemists have been embroiled in a scientific debate as to the paleoenvironmental nature and age of these water bodies (e.g., Buising, 1990; Spencer and Patchett, 1997; McDougall, 2008; Spencer et al., 2008, 2013; McDougall and Miranda Martínez, 2014; Gootee et al., 2016; O'Connell et al., 2017; Bright et al., 2018a, b; Dorsey et al., 2018) and the implications of these variable interpretations for the history of the CR, the integration of the river into the evolving Gulf of California, and regional tectonic history, including both the southern basin and range region and the Colorado Plateau (e.g., Bennett et al., 2016; Karlstrom et al., 2017; Pearthree and House, 2014; Crow et al., 2019a).

The most intense debate has focused on the origin of the basal Bouse Formation and exposures in the Blythe basin. This unit has variably been interpreted as having formed in marine (initially unaffected by CR water, but later estuarine) (Buising, 1990; McDougall and Miranda Martínez, 2014; Dorsey et al., 2018; Crossey et al., 2015) or lacustrine (Spencer and Patchett, 1997; Roskowski et al., 2010; Bright et al., 2016, 2018a, b) conditions, or in some hybrid of these scenarios evolving over time, based on conflicting evidence from fossils, isotope geochemistry, and sedimentology (Fig. 3). The fossil record of the lower Bouse Formation includes a bewildering mixture of apparently marine or estuarine (e.g., planktic foraminiferans, barnacles, and *Thalassinoides* trace fossils) and lacustrine (ostracodes, *Chara*, molluscs) fossils (Bright et al., 2018b). Sigmoidal bedding and other depositional features interpreted to be of marine tidal origin (O'Connell et al., 2017) were also interpreted by Spencer et al. (2018) to indicate a lacustrine origin. Isotopic data (C, O, and Sr) from Bouse carbonates uniformly point towards a continental water source, either similar to or modified from CR water, with little indication of a marine influence (Spencer and Patchett, 1997; Bright et al., 2016, 2018a, b). Two broad classes of models have arisen from these interpretations of the Blythe basin deposits, an incursion (or multiple incursions) of marine waters from an evolving proto-Gulf of California (McDougall and Miranda Martínez, 2014; Dorsey et al., 2018) or a "fill and spill" scenario of CR waters making their way downstream below the Grand Canyon by infilling a series of pre-existing basins as large lakes, which eventually infill with sediment and overtop their sill thresholds, allowing the CR to extend its length downstream towards an ultimate interconnection with the gulf (House et al., 2008; Spencer et al., 2013). Most participants in this debate now agree that Bouse Formation deposits in basins upstream from the Blythe basin, while displaying grossly similar stratigraphies and geochemical signatures to that basin, were all fully lacustrine through their history. Thus, it is only the Blythe basin that is currently at the core of this controversy.

In addition to this enigmatic history, the Bouse Formation, as well as the alluvial deposits that overlie it (e.g., Bullhead Alluvium, Howard et al., 2015; Chemehuevi Formation, Malmon et al., 2011; and Blythe Alluvium, Block et al., 2019; Fig. 1), house an outstanding and largely still untapped record of the history of both the CR since the Pliocene and climatic conditions during the early Pliocene. The latter is of particular significance, as this time period represents an initial episode of warming (e.g., Drury et al., 2018) towards the Piacenzian (mid-Pliocene warm period), which may be analogous to our modern anthropogenically driven transition to a warmer planet. Understanding the history of the CR, a critical water resource for desert southwestern North America, through its downstream Bouse Formation paleorecords is thus of value for society as a whole.

2 Workshop goals

It was through this lens of multiple lines of scientific interest in the Bouse Formation that a workshop was held 28 February–3 March 2019 in Parker, AZ, USA, to discuss the possibility of developing a scientific drilling project targeting this formation and its overlying CR-related strata. Over the course of 4 d, 33 participants debated whether, where, and how a drilling and coring campaign might proceed that could address (and perhaps resolve) the fundamental controversies surrounding the origin of the Bouse Formation in the Blythe basin and how high-resolution drill core records might improve our understanding of the paleoclimate and paleohydrology of this region.

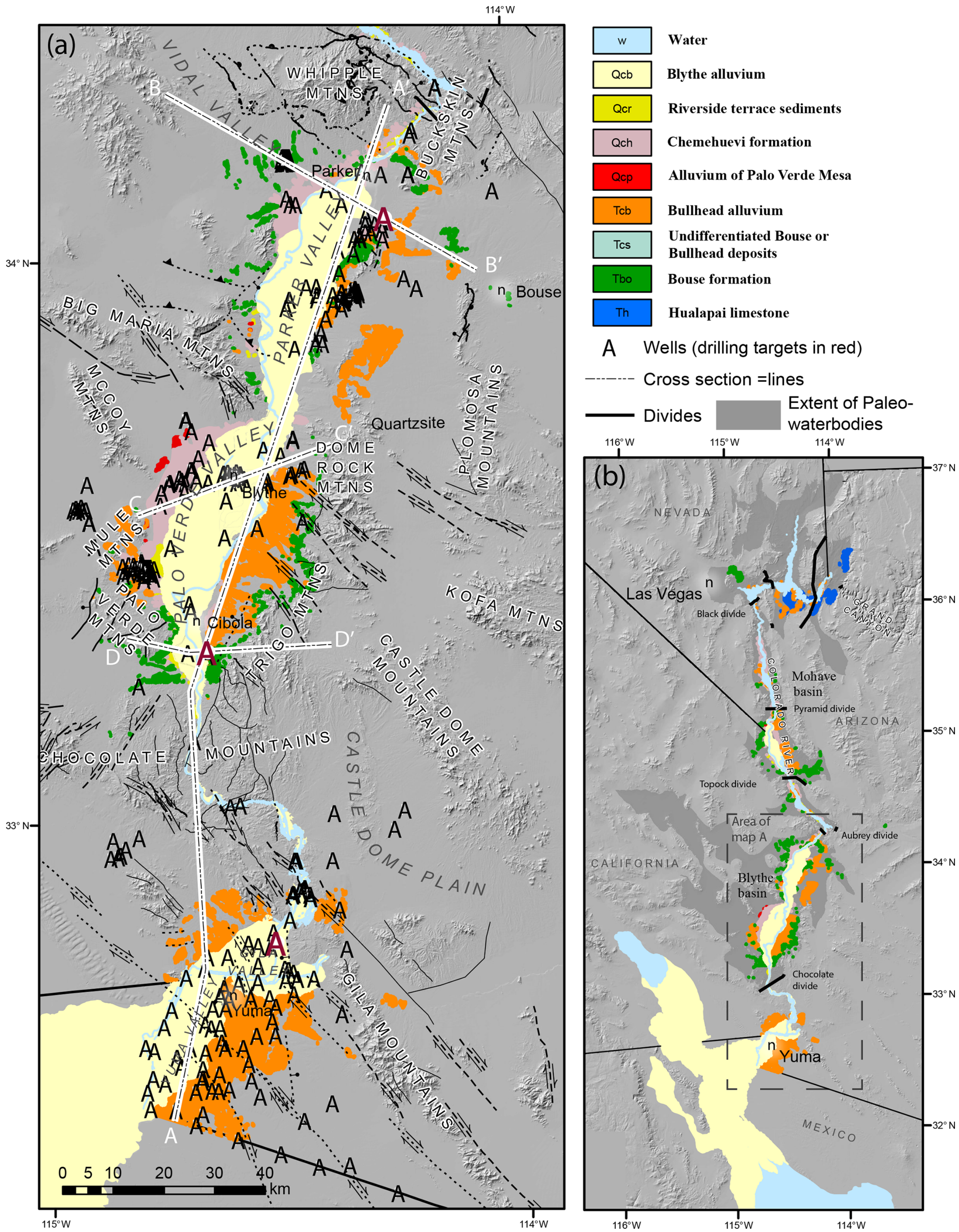

Figure 2. Geological index maps of **(a)** the Blythe basin study area and **(b)** the regional setting of the Blythe basin with respect to geologic elements of the Colorado River corridor and the Gulf of California, showing the reconstructed outlines of paleo-water bodies for the Bouse deposystem in darker gray and basin spillover locations with black lines. Panel **(a)** shows the outcrop distribution of stratigraphic units discussed in the text (modified from Crow et al., 2018), locations of prior water/geotechnical wells with cuttings/log records available for this study and cross sections illustrated in Fig. 4. Most discussion on target localities for drilling have focused on the well exposed and controversial Bouse Formation rocks of the Blythe basin. Potential and promising drill sites were also examined in the Yuma basin, south of the Chocolate Mountains basinal divide. Provisional drilling target areas are shown but additional site survey work is required prior to final site selections.

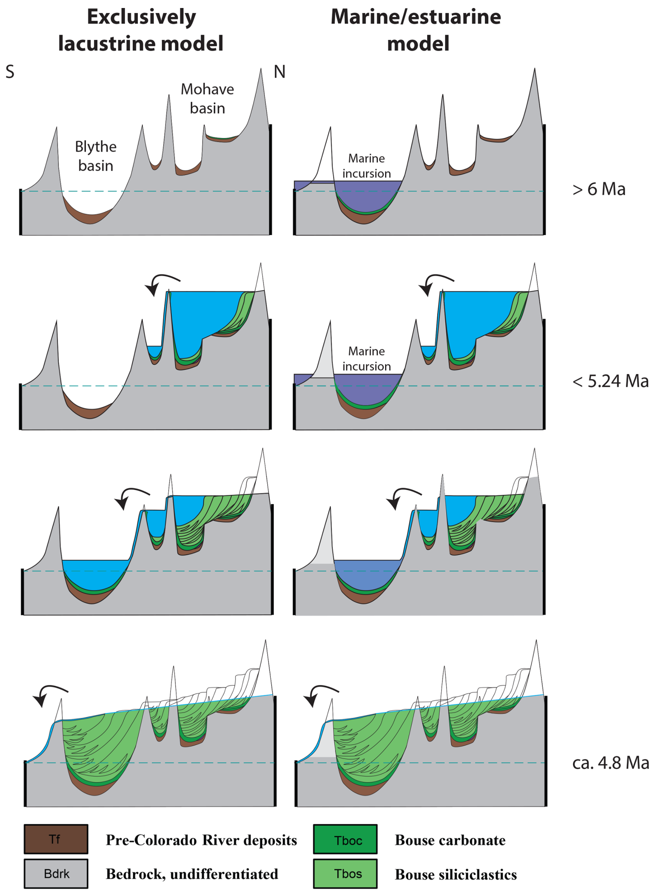

Figure 3. Alternative paleoenvironmental models for the Bouse Formation (after Pearthree and House, 2014). In the exclusively lacustrine model (Spencer and Patchett, 1997; House et al., 2008; Roskowski et al., 2010; Spencer et al., 2013; Bright et al., 2016, 2018a, b) the precursor internally drained Miocene basins and fanglomerate and playa deposits (brown) of the future lower Colorado River valley were successively flooded by a series of overspilling lakes, initially depositing the transgressive tufa, marl, and shelly carbonates of the lower Bouse Formation (dark green). Upstream basins were rapidly infilled by the progradational sediment bodies of the early Pliocene, upper siliciclastic Bouse (light green) (and later, Bullhead Alluvium), which eventually integrated the evolving Colorado River system into the proto-Gulf of California in the early Pliocene. Subsequent downcutting of the system resulted in the graded deposystem that has evolved since the early Pliocene. In the marine/estuarine model (Buising, 1990; McDougall and Miranda Martínez, 2014; Dorsey et al., 2018), arrival of the prograding Colorado River system into the Blythe basin was preceded in the late Miocene by a marine incursion, resulting in the formation of marine or estuarine bioclastic carbonates of the lower Bouse through one or more transgressive events. Subsequent arrival of the prograding and then downcutting Colorado River system then transformed the deposystem in a manner similar to the lacustrine model.

3 Paleohydrological and paleoclimatic research and education & outreach objectives of a lower Colorado River scientific drilling project

The workshop opened with a series of background talks intended to lay out our current understanding of the Bouse Formation, its tectonic setting, stratigraphy and sedimentology, paleontology, age, and geochemistry. Karl Karlstrom and Jacob Thacker (University of New Mexico) and Vicki Langenheim (USGS) discussed our current understanding from isostatic modeling of syn- and post-Bouse deformation, structural mapping, and geophysical surveys. Isostatic modeling is useful for estimating the original vertical position of key features related to the Bouse Formation, such as shorelines. Understanding the depth and shape of the Bouse depocenters (particularly those lying below sea level today) and their deformation history is critical for decision-making on appropriate drilling targets based on variable predictions of the marine incursion versus lake-fill and spill models. Understanding Bouse basinal strain history from outcrop fault geometries is key to understanding how tectonics has influenced lower CR deposits before, during, and after Bouse deposition. Regional gravity and magnetics data can also help inform us about potentially favorable depocenters for drilling thicker Bouse and post-Bouse stratigraphic sections.

The stratigraphy and sedimentology of the Bouse Formation have been a major focus of work for several research groups represented at the workshop, including Kyle House and Ryan Crow (USGS); Phil Pearthree and Brian Gootee (Arizona Geological Survey); Becky Dorsey, Brennan O'Connell, and Kevin Gardner (University of Oregon); and Colleen Cassidy (University of Arizona). House, Pearthree, and Gootee discussed the general stratigraphic framework of the early Pliocene (standing water and deltaic) Bouse Formation and post-Bouse (Pliocene–Holocene) alluvial deposits formed by the through-flowing Colorado River. They reviewed evidence from a series of N–S basins for the serial decantation of solute-rich CR waters with sediments stored in each basin until the delta wedge surmounts the outlet sill, at which point the outlet converted each successive lake into a valley, removing the drainage divide and allowing rapid incision in the upstream basin. The basal deposits of the Bouse in each successive basin are carbonates, sitting over buttressed unconformities at variable elevations (inferred by Pearthree and others to represent the rapid transgression of a series of lakes). This process was repeated multiple times as the CR worked its way southwards. This "decant–deposit delta–degrade–repeat" model (Fig. 3) provides a testable hypothesis for high-resolution drill core records. Above each basal carbonate is a sequence of siliciclastic fine-grained deposits, overlain by coarser-grained gravels and conglomerates that record the successive CR deltaic and fluvial aggradation. Dorsey, O'Connell, and Gardner presented the case for a marine (and specifically marine macrotidal) depositional setting for the lower Bouse carbonate member in the

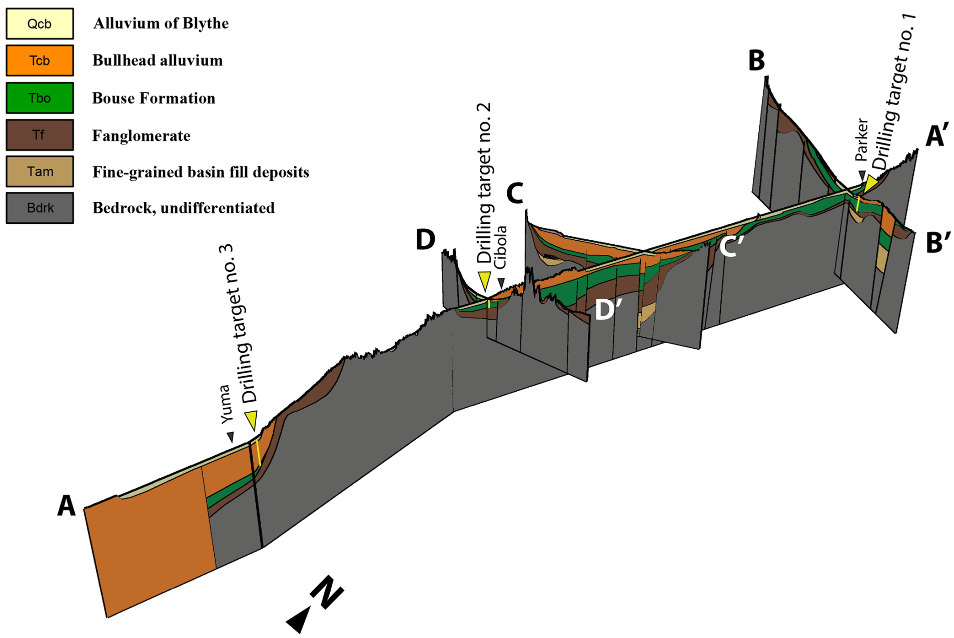

Figure 4. Fence diagram of Neogene strata in the lower Colorado River corridor (Blythe and Yuma basins) assembled from driller's log data from water and geotechnical wells. Scales are variable between cross sections but vertical exaggeration is 20×. Position of cross section lines shown in Fig. 2. Lengths of cross section lines are 210, 70, 40, and 40 km for Lines A to D, respectively. The 3-D subsurface geometry reconstructed from these well data, coupled with to-be-collected seismic reflection surveys immediately adjacent to high-priority drilling areas, will be used to select the final drill sites. Well control information is based on Cassidy et al. (2018).

Blythe basin, based on the presence of sigmoidal and compound dune bedforms, rhythmites inferred to have tidal periodicities, flaser bedding, and marine-like cements, as well as trace and body fossils discussed below. Cassidy discussed the joint USGS–UA project to digitize all existing log data (extensive but of variable quality) from research and water wells throughout the lower CR valley. These data are being used to develop realistic isopachs and structure maps of the Bouse, locating wells where the controversial basal carbonate was encountered and, from that information, predict optimal drilling targets for thick Bouse and post-Bouse sections (Fig. 4). Natalia Zakharova (Central Michigan University) discussed how downhole logging might be integrated into a future drilling campaign for the Bouse with drill core measurements of stratigraphy, and Anders Noren (University of Minnesota Continental Scientific Drilling Coordination Office) provided a "Drilling 101" primer for the many outcrop-focused geoscientists in the room.

Evidence from fossils and geochemistry weighs heavily in the Bouse debate but, like much else about the Bouse, is highly controversial. Kris McDougall-Reid (USGS) and Steve Hasiotis (University of Kansas) presented paleontological evidence from foraminiferans (some planktic species unknown from lakes) and trace fossils (e.g., burrowing shrimp typical of macrotidal flats) in support of a marine interpretation for the lower Bouse. McDougall also argued, based on biostratigraphic evidence, for a late Miocene age of the lowermost carbonates predating the arrival of CR waters. Scott Staratt discussed the potential for using diatoms to resolve the Bouse controversy. The one outcrop locality of Bouse which has been studied in detail for diatoms (well west of the main outcrop belt) contains a mix of marine and freshwater species. Similarly, Jessica Tierney (University of Arizona) discussed the potential for organic geochemical biomarkers to resolve the origins of the lower Bouse, as well as for paleoclimate studies discussed below. In contrast, Jordon Bright (Northern Arizona University) presented both stable isotope and faunal evidence from ostracodes indicating deposition of the lower Bouse in a consistently lacustrine water body, which was at times stratified and saline, but without detectable marine influence. Similarly, Laurie Crossey (University of New Mexico) studied the lowest Bouse carbonate unit, a "traver-tufa"-present ubiquitously draping pre-Bouse bedrock, which isotopically, morphologically (apparently deposited subaqueously), and paleontologically (presence of carbonate *Chara* algal casts) is consistent with a lacustrine origin interpretation.

Given the fill and spill framework (which is uncontested from the upstream basins) and evidence for marine incursions in the southern Blythe basin, it is clear that good geochronological control in multiple basins will be critical for evaluating the various models of how the Bouse Formation was formed. Ryan Crow and Keith Howard (USGS), Shannon Dulin (University of Oklahoma), and Steve Kuehn

(Concord University) discussed the most promising dating approaches based on Ar/Ar, magnetostratigraphy, and tephrostratigraphic data collected in basin margin outcrops to date. For example, recent advances in the combined application of $^{40}Ar/^{39}Ar$ dating of tephras and detrital sanidine with magnetostratigraphy were discussed that suggest the CR arrived in upstream basins between 5.24 and 4.6 Ma and at the Gulf of California between 4.8 and 4.63 Ma (Crow et al., 2019b); this is about half a million years later than previously suggested. Expanded sections, which could be provided by basin center drill cores of the Bouse and post-Bouse sediments, could provide an increased probability of collecting tephras and detrital sanidines in a stratigraphic context and a more complete and accurate paleomagnetic record. The fill-and-spill model for the CR all the way south to the uncontested marine-influenced region south of the Chocolate Mountain divide makes clearly differentiated geochronological predictions for the basal Bouse Formation and onset of CR-derived siliciclastics in each basin relative to the marine incursion model. Additionally, establishing the duration of Bouse deposition is critical to determining the timescale over which the lower Colorado River, a continental-scale river, became integrated with the ocean.

The potential of the Bouse Formation to provide a detailed paleoclimate record for the southwest during the early Pliocene had not been explored prior to this workshop. However, the age of the unit coupled with the potentially time-rich record ($\sim$ 100–500 kyr) during an intriguing period in Earth's history, make the Bouse a particularly compelling target for such studies. In addition to Tierney's suggested biomarker studies (in particular glycerol dialkyl glycerol tetraether (GDGT) investigations of paleotemperatures and compound specific isotopic studies of leaf waxes in the fine-grained Bouse units), the potential for fossil pollen studies of paleoclimate was discussed by Vania Stefanova (University of Minnesota), and clumped/triple oxygen isotopes were discussed by Karl Lang (Queens College) and Dan Ibarra (Stanford University), all of which seem promising approaches. Alison Smith (Kent State University) discussed other initiatives for obtaining Pliocene paleoclimate records from drill cores situated further north in western North America and how they might complement results that could arise from drill cores from the lower CR valley.

A Bouse–CR drilling project could have substantial and societally significant education and outreach dimensions. The lower CR is at the nexus of significant water rights controversies, following years of extended drought conditions in the CR basin, and both paleorecords of the CR and new subsurface information about post-Bouse aquifers could be of considerable interest. Local stakeholders from the Colorado River Indian Tribes and the Cibola National Wildlife Refuge (both of whose lands include potential drilling targets) and local municipalities were either present at the meeting and field trip or have been involved in discussions about the project to date. Amy Myrbo (University of Minnesota) discussed education and outreach programs (some derived from other successful past drilling and coring projects) that could serve as models for a future Bouse–CR-related project, focusing around training or display opportunities for local stakeholders' underserved communities which are chronically under-represented in STEM fields and especially the geosciences.

4 Recommendations of the workshop

Following the presentations discussed above, breakout sessions, plenary discussions, and a field trip to visit key outcrop and potential drilling sites allowed workshop participants to consider whether and where moving forward with a drilling campaign in the lower CR valley was warranted (Fig. 5). There was a strong consensus that a series of drill cores from depocenter sites along a N–S axial transect of the Blythe and adjacent basins could help address both the key outstanding paleoenvironmental controversies surrounding the Bouse Formation. They could also provide a seminal record of both early Pliocene paleoclimate for southwestern North America and the Colorado River's paleohydrologic history (Fig. 4). In all cases the objective would be to obtain cores where the Bouse Formation is both thick (maximum probable duration and temporal resolution) and fine-grained and where the controversial basal carbonate units are both present and fossiliferous. Fortunately, indications of all of these conditions can be obtained from the compiled water or geotechnical well driller's cuttings logs (no continuous cores are available). The specific targets which seem most promising (and to provide data unlikely to be recorded in basin marginal outcrops alone) are as follows.

1. *Southern Blythe basin*. This is probably the most critical drill site, as it would be in close proximity to many of the outcrops (e.g., Fig. 5b) that are most central to the Bouse debate. Because of its probable lower paleoelevation, an expanded section in the depocenter here would provide a record of the entire transgressive infilling of the basin by whatever type of standing water body was present.

2. *Northern Blythe basin*. A testable corollary of the fill-and-spill deltaic progradational model is that this area would provide a mostly(?) diachronous (earlier) phase of upper siliciclastic member deposition relative to the southern Blythe basin. In combination with the southern Blythe basin drill core record, an expanded fine-grained section, here it would also expand the duration of a high-resolution paleoclimate record (Fig. 5c).

3. *Northern Yuma basin*. Given adequate geochronologic control, a drill site immediately south of the Chocolate Mountain divide would allow unambiguous testing of the spillover hypothesis between this basin and the Blythe basin. It would also allow testing of the northerly

Figure 5. Bouse Formation. **(a)** Spectacular exposure (∼ 12 m outcrop height, looking west) of basal Bouse "traver-tufa" draping Cretaceous metavolcanic rock (pre-Cambrian protolith) bedrock near Mesquite Mountain, northern Blythe basin near Parker, AZ, looking east (photo credit: Andy Cohen). **(b)** Controversial (lacustrine or marine?) cross-bedded, bioclastic carbonate of the lower Bouse Formation at Big Fault Wash (looking north), near Cibola, AZ (photo credit: Kyle House). **(c)** Upper Bouse siliciclastic deposits from progradational infill by the Colorado River, Mesquite Mountain (looking east), near Parker, AZ (photo credit: Charles Ferguson).

directed marine incursion hypothesis of McDougall-Reid and Miranda Martínez (2014). No outcrops of the Bouse Formation exist in the Yuma basin, but it and its correlatives in the Imperial Formation have been identified and logged in numerous water and geotechnical wells (Olmsted et al., 1973)

4. *Mohave basin*. Going north from Blythe basin there was some interest in locating a drill core in this region. However, this would be a distinctly lower priority because many good Bouse depocenter outcrops exist in this region.

Workshop participants also agreed that prior to moving ahead with a full drilling proposal and campaign, additional site survey work was needed to both better identify the most optimal drilling targets and develop a "proof of concept" for likely paleoclimate and paleohydrological information that could be yielded from a study of the upper siliciclastic member of the Bouse Formation. Improved subsurface information beyond what is currently available from well control can be obtained through a shallow reflection seismic campaign, targeting the existing wells with the most optimal characteristics of thickness of fine-grained Bouse, presence of basal carbonate at or near the well, and logistical/access considerations. A proof-of-concept study would best be conducted at the relatively thick upper siliciclastic Bouse exposures on the west side of Mesquite Mountain, in the northern Blythe basin. The workshop participants recommended that both of these activities should be pursued through grant applications in the near future. Participants representing Colorado River Indian Tribes and local municipalities also made a strong case that these science activities be pursued in the context of a concerted effort to develop a meaningful education and outreach component to the project at each step of the way, beginning with the site survey work.

Data availability. No data sets were used in this article.

Author contributions. All authors contributed with the organization and planning of the workshop. CC and RC conducted the study of prior subsurface well data. AC wrote the paper with input from all authors. RC created Figs. 1–4, with input from AC and BG, and AC produced Fig. 5.

Competing interests. The authors declare that they have no conflict of interest.

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Northeast Atlantic breakup volcanism and consequences for Paleogene climate change – MagellanPlus Workshop report

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Abstract. The northeast Atlantic encompasses archetypal examples of volcanic rifted margins. Twenty-five years after the last ODP (Ocean Drilling Program) leg on these volcanic margins, the reasons for excess melting are still disputed with at least three competing hypotheses being discussed. We are proposing a new drilling campaign that will constrain the timing, rates of volcanism, and vertical movements of rifted margins. This will allow us to parameterise geodynamic models that can distinguish between the hypotheses. Furthermore, the drilling-derived data will help us to understand the role of breakup magmatism as a potential driver for the Palaeocene–Eocene thermal maximum (PETM) and its influence on the oceanographic circulation in the earliest phase of the northeast Atlantic Ocean formation. Tackling these questions with a new drilling campaign in the northeast Atlantic region will advance our understanding of the long-term interactions between tectonics, volcanism, oceanography, and climate and the functioning of subpolar northern ecosystems and climate during intervals of extreme warmth.

1 Introduction

The formation of continental margins is accompanied by a broad spectrum of magmatic activity ranging from little volcanism to the emplacement of a large igneous province (LIP) (Fig. 1). The reasons for this variability in magmatism are still disputed despite it being of large societal and economic importance. DSDP (Deep Sea Drilling Project) Legs 38 and 81 investigated the nature of the continental margins around the northeast Atlantic in 1974. ODP (Ocean Drilling Program) Legs 104, 152, and 163 in 1985, 1993, and 1995 established that volcanism plays a major role in continental breakup and instituted the concept of volcanic passive margins (Coffin and Eldholm, 1992; Eldholm et al., 2000). Breakup volcanism has since been identified as a major short-term climate driver that may have played a role in several mass extinctions (Eldholm and Thomas, 1993; Svensen et al., 2004, 2007). Magmatic intrusions can be of particular importance as they may have the potential to release large amounts of greenhouse gases through contact metamorphism in a very short time (Berndt et al., 2016), and it remains plausible that the magmatism associated with the breakup of the northeast Atlantic triggered the Palaeocene–Eocene thermal maximum (PETM) (Svensen et al., 2004; Minshull et al., 2016). The subsequent long-term tectonic evolution of the northeast Atlantic through the Paleogene and Neogene created an ocean gateway linking the Arctic Ocean to global circulation that is likely to have played a significant role in causing, or amplifying, environmental changes through its influence on ocean circulation (Laughton, 1975; Miller and Tucholke, 1983; Jakobsson et al., 2007; Coxall et al., 2018).

The underlying geodynamic processes that control the rifted margin structure are relatively well understood (e.g. Huismans and Beaumont, 2011). However, what drives and controls the degree of breakup magmatism remains disputed, despite the potential for breakup magmatism to affect tectonic deformation and to lead to abrupt climate change. The development of the concept of seismic volcanostratigraphy (Planke et al., 2000) represents a breakthrough that could lead to progress in understanding these processes. Seismic volcanostratigraphy is an interpretive framework that relates particular seismic facies to various volcanic emplacement environments, which has enabled large areas of volcanic margins to be interpreted from remote seismic data (e.g. Abdelmalak et al., 2016, 2019). This framework, developed through the joint analysis of results from ODP Legs 104 and 152 and large amounts of seismic data, enables seismic data to be used to infer the duration of volcanism, emplacement rate changes, subsidence history, and other aspects of volcanic margin formation that are tied to both the underlying geodynamic drivers of rift volcanism and the impact of that volcanism on the hydrosphere and atmosphere. Since 1996 there has been no dedicated scientific drilling leg to test the predictions that stem from seismic volcanostratigraphy and new seismic and potential field data (e.g. Abdelmalak et al., 2016; Planke et al., 2017), and thus important hypotheses remain untested that could be assessed with targeted drilling sites. These include the suggestion that northeast Atlantic breakup volcanism was short-lived enough to be a viable driver for the rapid early Paleogene climate change event and, by extension, other environmental crises throughout Earth's history.

In May 2018, we convened a MagellanPlus IODP–ICDP (International Ocean Discovery Program–International Continental Scientific Drilling Program) drilling workshop at GEOMAR, Germany, to develop new drilling proposals that would lead to an improved understanding of the nature of breakup volcanism and evolving Atlantic–Arctic gateways. This includes, for example, the question as to whether a link exists between hydrothermal venting of greenhouse gases formed by the heating of organic-rich sedimentary rocks by igneous intrusions and global negative carbon isotope excursions, such as those observed during the PETM. This would require dating the respective intrusions and the hydrothermal vent structures, sampling the Paleogene sediments and ash layers in high resolution, and constraining the extent of breakup-related volcanic successions and environments in which they were emplaced. Also required is an improved understanding of the nature of volcanic seismic facies units and whether they represent specific environmental conditions during the emplacement of the breakup volcanic extrusive successions and if they can be used to decipher the interaction of magmatic processes and (local) relative sea level changes. The early oceanic basins were likely restricted by igneous deposits which, at best, only allowed shallow surface water exchange with the Arctic Ocean and North Sea until the Miocene, after which the Greenland–Scotland Ridge and Fram Strait had deepened to allow for the exchange of cold dense waters, an important prerequisite for a deep Atlantic overturning circulation. Testing this hypothesis requires the coring of Eocene–Neogene sediments overlying the volcanic basement to produce a chronologic and palaeoenvironmental framework that constrains deep and surface water properties, including basin ventilation state and surface salinities.

Since the mid-1990s, major advances in seismic imaging, e.g. the development of three-dimensional seismic techniques and broadband processing, and their applications to volcanic provinces by the industry delineated the youngest, best-imaged, and most-accessible sub-surface structures. As a result, we identified a number of suitable IODP and ICDP drilling targets offshore in the northeast and northwest Atlantic and onshore in northern Denmark. Drilling these targets will allow us to better establish the sequence of events leading to the construction of the breakup-related igneous complexes. Furthermore, the drilling of the different seismic facies units would provide the ground truth about the predictions of seismic volcanostratigraphy. Together this information will constitute a step increase in our understanding of the underlying geodynamic processes of continental breakup and initial seafloor spreading, breakup-related magmatism, and the consequences of these processes on global environments.

2 Globally relevant aspects of studying breakup volcanism

2.1 Fundamental tectonomagmatic processes controlling breakup volcanism

The mechanism responsible for rift-related anomalous excess magmatic productivity is still debated (e.g. Lundin and Doré, 2005) although we have unsurpassed constraints on conjugate crustal structure between the Norwegian Jan Mayen–Greenland rifted margins in the northeast Atlantic and the western Greenland margin (Abdelmalak et al., 2019). The controversy centres on three competing hypotheses: (1) excess magmatism resulting from elevated mantle potential temperatures and mantle plume processes, (2) small-scale

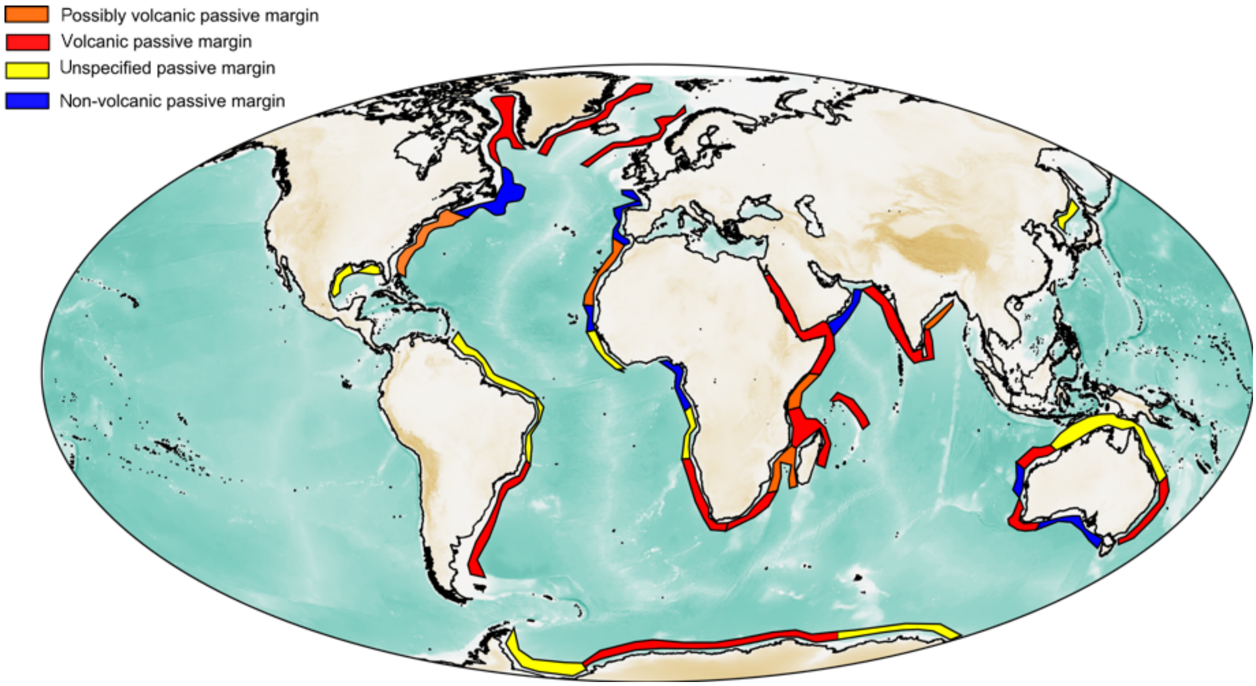

Figure 1. Distribution of the different types of passive margins around the world. The northeast Atlantic rifted margins are the type examples of volcanic rifted margins. Compiled from Menzies et al. (2002), Geoffrey (2005), Haupert et al. (2016), Jones et al. (2016), and Brune et al. (2016).

convection at the base of the lithosphere enhancing the flux of material through the melt window during rifting and mid-oceanic ridge spreading, and (3) depth-dependent extension with wide margins promoting excess magmatic accretion. Bonatti (1990) proposed an alternative for the formation of excess magmatism based on mantle heterogeneities in addition to these geodynamic end-members. Whereas the mantle plume mechanism requires anomalous high temperatures resulting in high degrees of melting during asthenosphere upwelling, small-scale convection operates without elevated potential temperatures. In contrast small-scale convective instabilities at the base of the lithosphere are inherently connected to and produced by the rifting process (Keen and Boutilier, 2000).

Continental breakup may be associated with extensive volcanism over large distances along the strike of the rifted margins as exemplified in the northeast Atlantic (Fig. 2). The causes for the anomalous magmatic activity and the implications on the palaeoenvironment are, however, still debated. Magmatic products (Fig. 3) emplaced along these volcanic rifted margins have four major characteristics. (1) Wedges of seaward-dipping reflectors (SDRs) and associated volcanic seismic facies units, interpreted as massive sub-aerial and submarine lava flows and volcaniclastic sediments, are found on both sides of the ocean–continent boundary. (2) They have extensive sill and hydrothermal vent complexes emplaced in organic-rich sedimentary basins along the incipient breakup axis. (3) Thick high-velocity bodies in the lower crust along the ocean–continent boundary are commonly interpreted as magmatic underplated material. (4) The magmatic crust at these margins often exceeds 20 km, more than 3 times as thick as normal oceanic crust produced by passive upwelling of the normal potential temperature mantle. It appears that volcanic rifted margins require mantle material that is either (1) anomalously hot, (2) anomalously fertile, (3) actively upwelling at rates higher than the plate half-spreading rate, or some combination of these factors. We propose to test the following hypotheses with the envisioned new IODP drilling campaign.

2.1.1 Hypothesis 1a: mantle plume involvement produces excess magmatism

The association of the northeast and northwest Atlantic volcanic rifted margins with the Iceland hotspot has strongly influenced the discussion of the causes for the excess magmatic productivity (e.g. Bijwaard and Spakman, 1999; Ritsema et al., 1999; Foulger et al., 2001; Montelli et al., 2004) and has led to the hypothesis that excessive magmatic productivity, which resulted from high mantle temperatures, was caused by a mantle plume (Brown and Lesher, 2014; McKenzie and Bickle, 1988; White and McKenzie, 1989). Various plume structures have been suggested including (1) a plume head impinging on the base of the lithosphere and (2) rising vertical plume sheets. Numerical models predict that a plume, with a potential temperature of possibly 50–300 °C higher

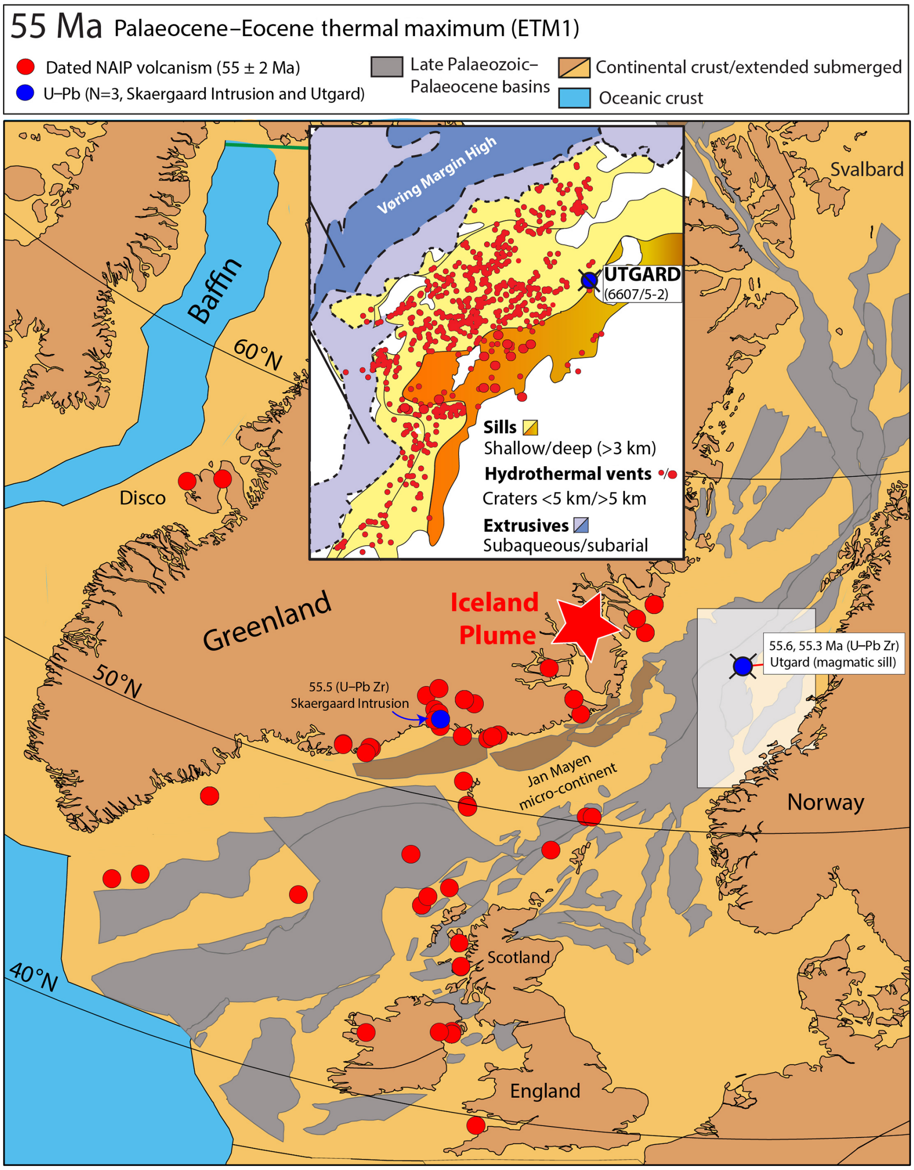

Figure 2. Reconstruction of the northeast Atlantic at 55 Ma with the distribution of dated (57–53 Ma) onshore and offshore sample locations (red filled circles) for the North Atlantic Igneous Province, the location of the Iceland Plume with respect to Greenland (Torsvik et al., 2015), and rift basins developed from the late Palaeozoic to the Palaeocene (Faleide et al., 2010). The inset map demonstrates the extensive sill and hydrothermal vent complexes in the Vøring Basin off the shore of Norway (see white box in main map) and the location of the 6607/5-2 Utgard borehole, where magmatic sills intruding organic-rich sediments are dated to 55.6 and 55.3 Ma (U–Pb zircon; Svensen et al., 2009). From a database of many hundreds of dated volcanics and intrusions there are only six U–Pb ages, ranging from 62.6±0.6 Ma (Antrim lower basalt in Ireland) to 56.02 Ma (Skaergaard intrusion in eastern Greenland).

than the surrounding mantle, can produce large quantities of melt (White and McKenzie, 1995; Hole and Millett, 2016; McKenzie and Bickle, 1988). Larsen and Saunders (1998) proposed that the opening of the northeast Atlantic rift allowed a sheet of hot plume material to spread along the rift for as much as 2700 km from south of Greenland to the Barents Sea. Recent seismic tomography confirms that the Iceland anomaly extends to the lower mantle (e.g. French and Romanowicz, 2015; Jenkins et al., 2016).

2.1.2 Hypothesis 1b: active upwelling without a thermal anomaly

Active mantle upwelling without a thermal anomaly provides an alternative mechanism for excess magmatism at volcanic rifted margins involves. Active upwelling is defined as upwelling of mantle at a rate higher than the half spreading rate of the rift zone (Holbrook and Kelemen, 1993). Mutter et al. (1988) first suggested that small-scale convection induced

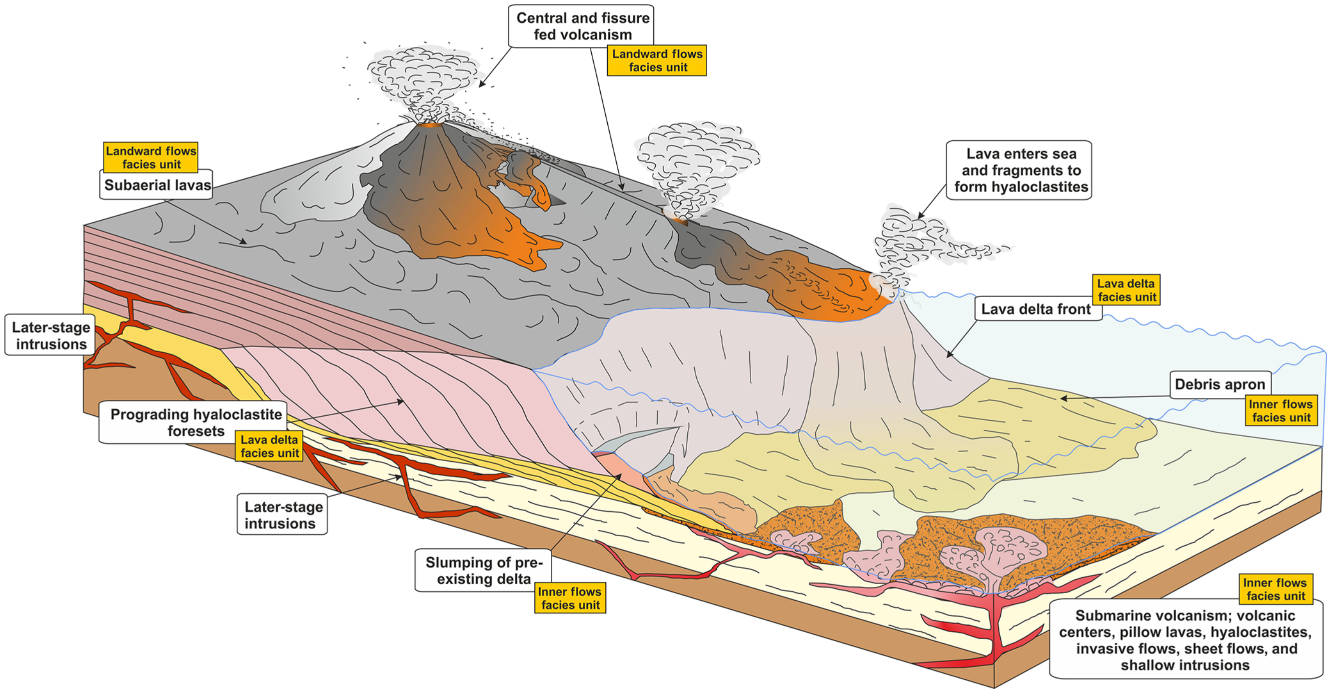

Figure 3. Breakup volcanism in the North Atlantic resulted in extrusion (pink and orange colours) and intrusions (red) of magmas into the sediments basins and led to the development of lower crustal bodies with particularly high seismic velocities called underplating (not shown) (Abdelmalak et al., 2016).

by lateral temperature gradients may provide an enhanced flux of material into the region of partial melting, thereby increasing magmatic activity in the absence of mantle potential temperatures elevated by an external influence. While this hypothesis has attracted considerable attention (Mutter et al., 1988; Boutilier and Keen, 1999; Keen and Boutilier, 2000; Nielsen and Hopper, 2004; Simon et al., 2009), the relative importance of active upwelling in the evolution of rifted volcanic margins is still debated (Holbrook et al., 2001; Korenaga et al., 2000, 2002).

2.1.3 Hypothesis 1c: excess magmatism owing to an enriched mantle source

Major element source heterogeneity may also contribute to anomalously high melt production during continental breakup (Davies, 1983; Zindler et al., 1984; Allègre and Turcotte, 1986; Allègre and Lewin, 1995; Morgan and Morgan, 1999; Kellogg et al., 2002; Meibom and Anderson, 2004; Albarède, 2005). The mantle is characterised by significant chemical and isotopic heterogeneity and appears to be a heterogeneous assemblage of depleted and enriched peridotite, as well as recycled subducted oceanic crust, the lithosphere, and sediments. Inherited enriched domains in the sub-lithospheric mantle with anomalously low melt temperatures may therefore deliver more melt during their ascent beneath the extending lithosphere and at the ridge axis.

These end-member processes have distinct characteristics and diagnostic features that may be used to differentiate their relative roles during volcanic margin formation. Plume-related anomalous high mantle temperatures will result in high melt fractions, high-pressure melting, and distinct geochemical characteristics (e.g. He and Sr–Nd isotope anomalies). Active upwelling (small-scale convection), conversely, without a thermal anomaly will result in a low average pressure of melting (Holbrook et al., 2001; Korenaga et al., 2002), low degrees of melting, and geochemical signatures closer to mid-ocean ridge basalt (MORB). Furthermore, the plume mechanism predicts that the largest excess magmatic productivity will occur close to the plume centre and there will be local structural control on melting. Active upwelling caused by small-scale convection on the contrary is completely controlled by the local geometry of rifting, its consequences for local perturbations in thermal structure, and the local viscosity and density structure of the mantle lithosphere and sub-lithospheric mantle. A fertile source should result in a high average pressure of melting and distinct isotope geochemistry of the melts indicating an enriched source. Information on the temporal and spatial variations of the mantle potential temperature and active upwelling can be used to constrain models of rift dynamics, rift-related convection, and plume–rift interaction (Brown and Lesher, 2014).

In spite of 30 years of research into the reasons for excess magmatism during the breakup of continents, it has not been possible to determine which of the three competing hypotheses (1a–1c) is correct. Therefore, we propose a new approach to test the hypotheses that goes beyond the largely geochemical approaches that have been employed in the past. By drilling the various breakup related volcanic facies units, we will produce the information on the timing, the rates of volcanism, and the vertical movements of the Norwegian margin necessary to feed geodynamic models that are able to distinguish between the competing hypotheses.

We concluded during the workshop by affirming that it is important to test a further hypothesis that will deal with the consequences of breakup magmatism.

2.1.4 Hypothesis 2: voluminous emplacement of magma in organic-rich sedimentary basins and basaltic eruptions may trigger global warming

The magma volume, eruption duration, and emplacement environment are critical parameters for the palaeoenvironmental implications of LIPs. Svensen et al. (2004) proposed a new hypothesis to explain how LIPs could trigger global environmental crises. The basic feature of this hypothesis is that magma emplaced into organic-rich sedimentary sequences leads to heating of the host rock and generation of large volumes of greenhouse gases, most importantly CH_4 and CO_2 (Aarnes et al., 2010, 2011). The gas generation may cause an overpressure build-up and formation of so-called hydrothermal vent complexes (Svensen et al., 2004; Reynolds et al., 2017), releasing fluids and sediments to the hydrosphere and atmosphere (Aarnes et al., 2015). This hypothesis may be tested by collecting climate proxy data and sampling proximal Palaeocene–Eocene deposits both in the Vøring Basin and in Denmark (e.g. Svensen et al., 2004; Frieling et al., 2016). The proximal nature of the Vøring Basin to the volcanic and magmatic sequences of the North Atlantic Igneous Province (NAIP) could allow for the differentiation between volcanic and thermogenic origins of gases, as differences between sub-aerial and subaqueous emissions of key magmatic tracers such as tephra and mercury have a primary control on their subsequent dispersal (Jones et al., 2019). Comparisons of this proximal dataset with distal sedimentary systems would then offer insights into the relative timing of extrusive and intrusive magmatic activity and its temporal relationship to climate change events. The sedimentary record may also provide insight into the long-term Palaeocene climate variation in a proximal setting during the early phase of the NAIP and potential palaeoclimate links to basaltic explosive and effusive eruptions.

2.2 Effects of volcanism on climate change

Volcanoes play a key role in many global element cycles, helping to replenish and regulate atmospheric and oceanic chemistry over time. However, volcanism is episodic and stochastic in nature, and elevated periods of activity in Earth history will impact the carbon cycle (Jones et al., 2016). Periods of elevated volcanism such as the emplacement of the NAIP often coincide with considerable environmental perturbations such as the PETM (Fig. 4), suggesting a possible causal relationship (Bond and Wignall, 2014). The total volume of magma emplaced during the Paleogene is estimated to be $6–10 \times 10^6$ km^3 (Saunders et al., 2007). NAIP activity is interpreted as occurring in two main pulses of activity:

1. A pre-breakup phase of continental flood basalt volcanism was largely erupted through and onto continental crust.
2. The main, more-voluminous phase of thick lava flows and widespread intrusions is closely associated with the breakup of the northeast Atlantic Ocean (Saunders et al., 2007; Storey et al., 2007b; White and McKenzie, 1995).

The formation of the NAIP delivered considerable volumes of greenhouse gases to the atmosphere, both in the form of direct volcanic degassing and explosive discharge of thermogenic gases generated by contact metamorphism around magma intrusions into sedimentary basins (Svensen et al., 2004). Therefore, the NAIP is one of the primary contenders for causing the steady warming and, potentially, also numerous hyperthermal events in the Paleogene (e.g. Cramer et al., 2003; Lourens et al., 2005), either by direct forcing and/or as an instigator of positive climate feedbacks such as methane hydrate melting (e.g. Lunt et al., 2011).

The relationship between the NAIP and Paleogene climate remain a topic of intense debate. The extreme greenhouse conditions of the PETM occurred at ca. 55.8 Ma (Charles et al., 2011), which coincides with the second major pulse of activity from the NAIP (Storey et al., 2007a). However, there are significant gaps in our understanding of the timing and volumes of greenhouse gas fluxes from both volcanic and intrusive NAIP activity. A robust geochronology of the NAIP activity is currently hindered by the limited number of accurate radiometric ages and relatively limited ability to trace LIP volcanism in sedimentary archives. At present, the available modern geochronological data are restricted to $^{40}Ar/^{39}Ar$ mineral ages and a few U–Pb ages for subvolcanic intrusions (Larsen et al., 2016; Storey et al., 1998, 2007b; Svensen et al., 2010; Wilkinson et al., 2016). Significant hiatuses can be observed in between the two phases of magmatism in the late Palaeocene (Larsen et al., 1999; Storey et al., 2007b), although the apparent timing of these repose periods seems to vary across the NAIP. In eastern Greenland there is corroborating evidence that voluminous volcanism occurred in the late Palaeocene and early Eocene. The initial emplacement of the Skaergaard intrusion occurred at 56.02 Ma (Wotzlaw et al., 2012), and a geobarometer study using amphiboles suggests that the intrusion was buried by 5.3–6.3 $\pm$ 2.7 km of flood basalts as it crystallised (Larsen and

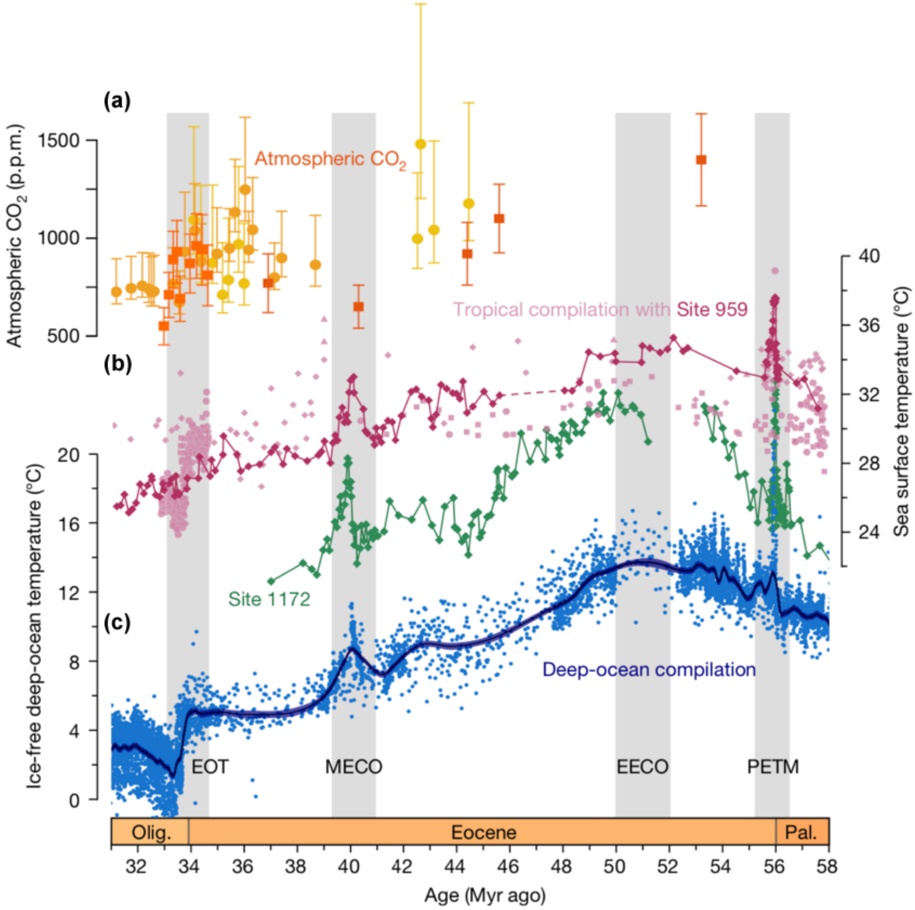

Figure 4. Eocene global climate evolution (redrawn from Cramwinckel et al., 2018). **(a)** Compiled atmospheric CO_2 based on boron isotope and alkenone stable carbon isotope fractionation data. **(b)** High-latitude (green) and tropical (purple and pink) sea surface temperature records based on organic (TEX_{86}) and various carbonate-based (Mg/Ca, oxygen isotope, and clumped isotopes) inorganic geochemical proxy data. **(c)** Ice-free deep-ocean temperature based on high-resolution oxygen isotope data of benthic foraminifera.

Tegner, 2006). This estimate equates to around 100–300 kyr, representing a huge outpouring of lava that began ∼ 200 kyr before the PETM (Charles et al., 2011). Moreover, a distinctive tephra layer in the uppermost part of the East Greenland flood basalts (Heister et al., 2001) is indistinguishable in both chemistry and age to a prominent tephra horizon found in the North Sea and in Danish strata (Storey et al., 2007a). The corrected Ar/Ar radiometric age is $\sim 55.6 \pm 0.12$ Ma for this tephra (Lars Augland, personal communication, 2019), indicating a 400 kyr time interval for the East Greenland flood basalts that encompasses the PETM.

There is also mounting evidence for considerable magmatic intrusions during this time interval. Vent structures form at the edges of sill intrusions due to overpressure generated by pore fluid boiling and/or gas generation from contact metamorphism (Aarnes et al., 2015). The resulting explosions are capable of ejecting gases into the atmosphere, even from submarine vents (Svensen et al., 2004). Many submarine hydrothermal vent complexes have been identified in the Norwegian Sea (Planke et al., 2005), in the Faroe–Shetland basin (Hansen, 2006), and on the northeastern Greenland margin (Reynolds et al., 2017), which suggests that these features were widespread along the proto-northeast Atlantic margins. The majority (∼ 95 %) of the vent complexes in the Vøring and Møre basins terminate at the horizon between Palaeocene and Eocene strata, with the remainder terminating within the Palaeocene sequence (Planke et al., 2005), with some examples penetrating through earlier volcanic events (Angkasa et al., 2017). The only drilled vent complex is dated to within the PETM (Frieling et al., 2016), whereas a zircon U–Pb age from a sill in the Vøring Basin was dated to ca. 55.6 Ma (Svensen et al., 2010). It therefore appears likely that the emplacement of sills led to considerable hydrothermal venting of gases around the time of the PETM.

While both volcanism and contact metamorphism degassing appear to coincide with the global warming events of the late Palaeocene and early Eocene, there remain considerable unknowns in terms of temporal development and potential gas fluxes from these sources. Moreover, it is currently difficult to separate the effects of volcanism and contact metamorphism in order to assess their relative forcing on the climate system. There are a number of possible ways to improve the geochronology and relative importance of each flux in the Paleogene. The acquisition of core material through continuous strata in close proximity to the NAIP would be an invaluable asset in deciphering the relative importance of these two processes. While both volcanism and contact metamorphism release greenhouse gases, gases from the latter are partly produced from sedimentary organic matter and therefore have much more depleted δ^{13}C values. The eruptions from hydrothermal vent complexes are also more likely to transfer co-erupted metals such as mercury to the overlying water column, so large variations in metal concentrations in sediments proximal to vent complexes would suggest periods of elevated degassing driven by sill intrusions (Jones et al., 2019).

3 North Atlantic Igneous Province

While many continental margins may be considered volcanic rifted margins (e.g. South Atlantic, Arabian Sea, and northwestern Australia) the northeast Atlantic is by far the most intensely studied volcanic rifted margin. As an early frontier for hydrocarbon exploration this margin attracted also scientific attention and for the past seven decades an enormous amount of geophysical and drilling data were collected culminating in five DSDP and ODP legs: Leg 38 (1974) – Vøring (Talwani and Eldholm, 1977); Leg 81 (1981) – Rockall (Roberts et al. 1984); Leg 104 (1985) – Vøring (Eldholm et al. 1987, 1989); Leg 152 (1993) – southeastern Greenland (Larsen et al. 1994; Larsen and Saunders, 1998); Leg 163 (1995) – southeastern Greenland (Larsen et al., 1999; Duncan et al., 1996). Apart from the enormous amount of available data and a priori information, the North Atlantic Igneous Province also lends itself to the study of breakup volcanic processes because both conjugate margins can still be studied and because rifting occurred over a wide area trapping terrestrial sediments. This results in a situation in which the breakup volcanic successions are nearer to the seafloor than on other volcanic margins, which makes it easier to study them by geophysical methods and drilling.

The northeast Atlantic rift system developed as a result of a series of rift episodes succeeding the Caledonian orogeny that ultimately led to continental breakup and passive margin formation in the Palaeocene–Eocene (e.g. Talwani and Eldholm, 1977; Eldholm et al., 1989; White and McKenzie, 1989; Skogseid et al., 2000). The conjugate Norwegian Jan Mayen–Greenland margins are now very well covered by 2-D and 3-D reflection and refraction seismic surveys, by potential field and heat flow data, and by borehole data that allow a refined structural and stratigraphic framework (Figs. 1, 2, and 3) (e.g. Gudlagusson et al., 1988; Lundin and Doré, 1997; Brekke, 2000; Raum, 2000; Tsikalas et al., 2001, 2005; Osmundsen et al., 2002; Gernigon et al., 2003; Ren et al., 2003; Hamann et al., 2005; Mjelde et al., 2005a; Breivik et al., 2006).

The Norwegian margin is segmented along strike by the northwest-trending Jan Mayen Fracture Zone and the Bivrost Lineament, which separate from south to north the Møre, Vøring, Lofoten–Vesterålen, and Barents Sea margin segments on the Norwegian side and their conjugates at the Jan Mayen microcontinent and off of northeastern Greenland (Figs. 1 and 2). Margin segments are characterised by strongly different tectonomagmatic styles and sediment distributions (Fig. 4) (Doré et al., 1999; Berndt et al., 2001; Eldholm et al., 2002). The largest magmatic accumulation is observed in the Vøring segment with decreased volumes to the south and north. In the southern segment, passive margin formation and oceanic spreading were accommodated by the Aegir Ridge between the Møre and Jan Mayen (at the time still connected to Greenland) conjugate margins in the Palaeocene–Eocene. The Aegir Ridge was abandoned in the late Oligocene and the Jan Mayen micro-continent separated from Greenland during the development of the Kolbeinsey Ridge (Talwani and Eldholm, 1977; Nunns, 1982; Skogseid et al., 2000; Müller et al., 2001).

Rifting and passive margin formation in the northeast Atlantic was accompanied by strong volcanic activity (White and McKenzie, 1989; Eldholm et al., 1989; Eldholm and Grue, 1994; Larsen and Saunders, 1998). Along the northeast Atlantic rifted margins, evidence for extensive magmatism is provided by SDRs, magmatic intrusives, and high-velocity bodies at the base of the continental crust underlying the ocean–continent boundary which in the distal margin are unequivocally interpreted as a magmatic underplate (Talwani and Eldholm, 1977; Roberts et al., 1984; Eldholm et al., 1989; Larsen and Saunders, 1998; Berndt et al., 2001; Mjelde et al., 2005b; Planke et al., 2005).

The ODP drilling of the Vøring Margin (Leg 104) and off of southeastern Greenland (Legs 152 and 163) recovered volcanic rock successions that erupted during the initial stages of the opening of the northeast Atlantic (Fig. 5). The drilled rocks (Legs 152 and 163) range from pre-breakup continental tholeiitic flood basalt, through syn-breakup picrite, to oceanic-type basalt that form the main part of the SDRs (Fitton et al., 2000). The oceanic-type lavas show an increasing degree of melting and contribution from asthenospheric mantle sources with time (Fram et al., 1998; Fitton et al., 1998). The thickness of igneous crust accreted at the southeastern Greenland continent–ocean boundary increases from about 18 km in the south to about 30 km near the Greenland–Iceland Rise (Holbrook et al., 2001). Similarly, geochemical enrichment of volcanics of the East Greenland Margin (e.g. chondrite-normalised $(Ce/Y)_N$ and isotopes; Fram et al., 1998; Fitton et al., 1998; Tegner et al., 1998; Brown and Lesher, 2014) increases from south to north. The correlation of crustal thickness and compositional enrichment suggests a combination of changes in source composition, source temperature, and/or melting dynamics. It is not known if a sim-

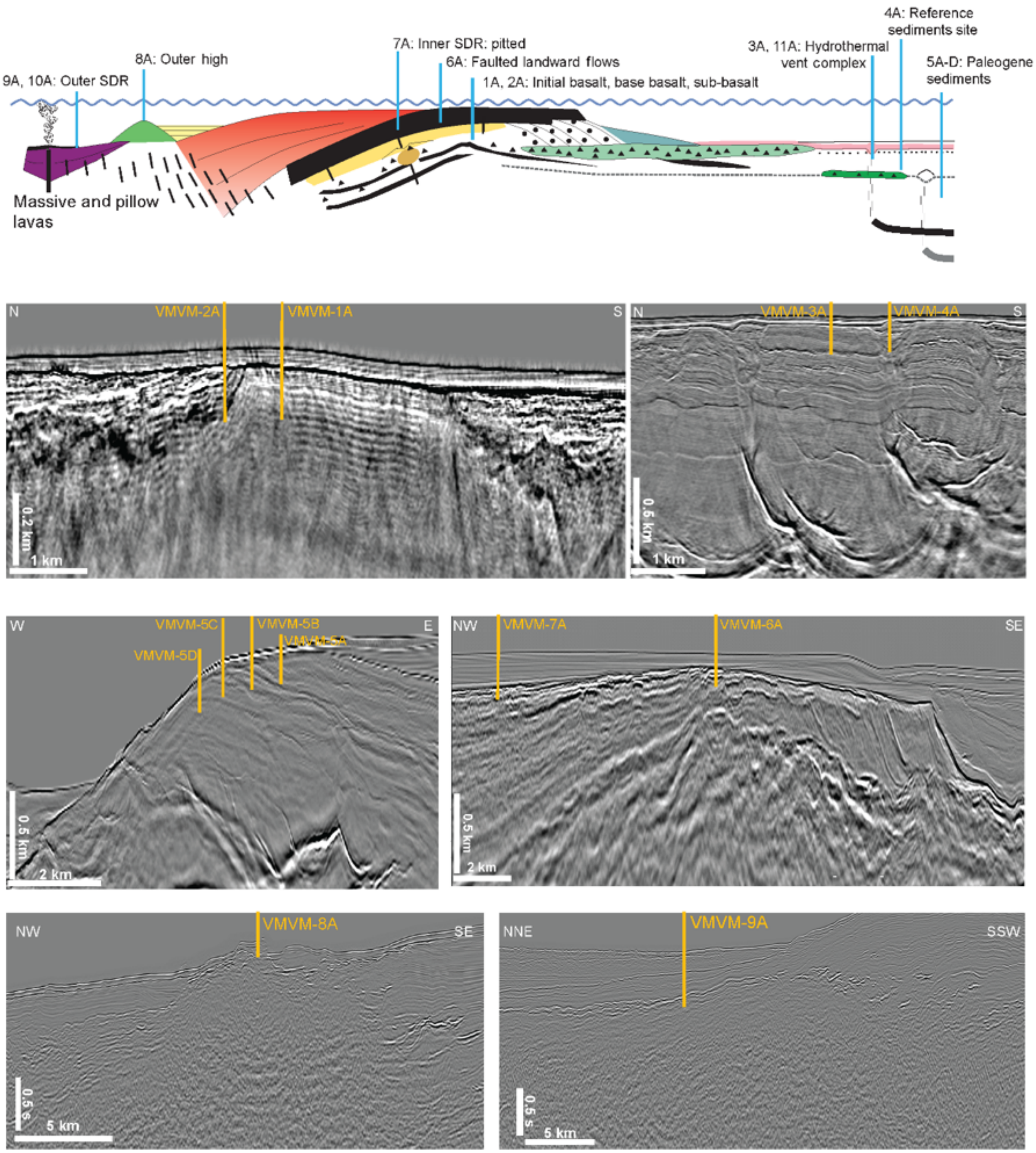

Figure 5. Volcanic seismic facies unit sketch (after Planke et al., 2000) showing schematic location of potential drill sites (top) and modern seismic reflection data showing sites proposed in IODP proposal 944 resulting from the workshop. In sequence (grey panels: left to right, top to bottom) these will test the landward flows, hydrothermal systems linked to sill intrusions, the host rock, the seaward dipping reflectors, the outer high facies, and the outer seaward dipping reflectors (data courtesy of TGS, more information at https://www.tgs.com/, last access: 17 November 2019).

ilar correlation of crustal thicknesses and magma compositions exists along the Norwegian margin. To establish the relationship between the chemistry of the volcanics and crustal configuration would be a milestone of the proposed investigations. Geochemical data (Fig. 5) show strong chemical and isotopic similarities between the "Upper Series" from the Vøring Plateau and southeastern Greenland. In contrast, the "Lower Series" from both areas are fundamentally different from each other in many aspects. These differences point to substantial differences in either the pre-breakup lithosphere composition at the two localities or to different styles of mantle–crust interaction.

4 Drilling strategy and potential sites

During the workshop discussions focused on a potential drilling strategy to maximise knowledge gain from a new drilling campaign. The mid-Norwegian margin is well suited for scientific drilling of Palaeocene and lower Eocene sequences as the post-breakup sediment cover is thin (commonly less than 200 m), and abundant new 2-D and 3-D seismic data exist. The conjugate northeastern Greenland margin and the Jan Mayen Ridge have much thicker post-breakup sediment packages (commonly 1–2 km) and regional 2-D seismic coverage, but several deep drilling sites have been identified. Few basement drilling targets were identified in the northwest Atlantic due to kilometre-thick post-breakup sediment units. The Limfjorden region, on the shore of Denmark, is however a promising complementary onshore drilling area, as Palaeocene and lower Eocene sediments and ash layers are outcropping here and accessible for sampling by boreholes of 500–800 m.

On the mid-Norwegian margin the most promising approach would be to drill 5 to 10 shallow holes along one along-strike and one cross-strike margin transect, including volcanic and high-resolution Paleogene sedimentary sites. The temporal and spatial sampling of volcanic rocks is important to constrain melting conditions and plume influence on magmatism. The holes should provide samples of the main volcanic terrains and ages (61–50 Ma). Geochemical data can provide proxy data for the melting temperature and dynamics in space and time. Furthermore, the data can be used to assess mantle heterogeneities, lithospheric structures (e.g. transform margins), and lithospheric contamination. Geochronological data combined with geophysical data are essential to provide constraints on how magma fluxes vary along the strike and across the margin. These are all crucial parameters required to model melting processes.

To determine the relative vertical movement of the margin we propose to test the nature of volcanic seismic facies units. The seismic volcanostratigraphic interpretation suggests that the emplacement environment can be determined from the seismic data (Planke et al., 2000; Berndt et al., 2001; Abdelmalak et al., 2016). Previous drilling on the Vøring Margin (Hole 642E) has documented that the inner SDR and landward flows represent sub-aerially emplaced lava flows. However, to date, no SDR reflections have been drilled by IODP or its predecessors. Furthermore, the nature of the inner flows, lava delta, outer high, and outer SDR has not been documented by scientific boreholes. In the model of Planke et al. (2000) the outer SDRs are emplaced in a deep marine environment; the outer high is in a shallow marine environment; the lava delta is in a coastal environment; and the inner flows are in a deep marine environment. The landward flows, lava delta, and inner flows are thought to represent a transition from the sub-aerial to subaqueous domains (Abdelmalak et al., 2016). The documentation of the emplacement environment of the different facies units will provide important control on the vertical motions of the volcanic eruption centres in space and time, which are important parameters for modelling margin dynamics.

Direct observation of the palaeoenvironment by the sampling of Paleogene sediments will help to determine the relationship between magmatism and the palaeoenvironment. Several potential drilling sites have been identified along the Vøring Transform Margin and on the shore of Denmark. Analyses will include the radiometric dating of tephra layers and collection of volcanic proxy data such as metal enrichments and evidence of hydrothermal vent complex ejecta. These volcanic proxies will be integrated with palynology and organic molecular proxies to reconstruct palaeo-sea-surface and palaeo-land-air temperatures and palaeoenvironmental changes.

An across-strike margin transect is proposed in the central Vøring Margin segment, and it could consist of four sites. This transect is located in a typical volcanic rifted margin setting and will cover the entire age range of breakup volcanics to understand syn- and post-breakup volcanism, melting, and margin dynamics. The inner two sites are located on modern 3-D seismic profiles, whereas the outer two sites are located on 2-D seismic profiles. The holes are complementary to the existing DSDP and ODP holes in the region.

The aim of the along-strike transect is to sample volcanic rocks in the northern part of the Møre Margin, the Kolga High. This structure has recently been covered by high-quality 3-D industry seismic data, and it documents very thin basalt above a non-reflective structural high. The two sites aim at sampling the sub-basalt and initial basalt deposits on this margin segment. The along-strike profile will include the existing deep ODP 642 Site on the southern Vøring Margin, DSDP Sites, and the two proposed site on the Vøring Marginal High.

Two high-resolution Paleogene sediment sites are proposed along the Vøring Transform Margin. The Paleogene is within the 200 m b.s.f. limit in two places, the northern Kolga High and the Mimir High. Two holes are proposed on the northern Kolga High to ensure relatively complete coverage of the sequence. Four slightly offset holes are proposed on the Mimir High. Here, the Palaeocene and lower Eocene sediments are dipping gently northwards and offset drilling may provide a more complete sampling of the succession. In addition, two boreholes in the Limfjorden area, northern Denmark, targeting Palaeocene and lowermost Eocene sedimentary strata and ash layers, are proposed in a complementary ICDP proposal.

5 Secondary objectives

5.1 The role of oceanographic gateways on the onset of Atlantic meridional overturning circulation

A significant consequence of the tectonic opening of the northeast Atlantic during the Paleogene and Neogene is the creation of ocean gateways linking the Arctic Ocean to the Atlantic through the Greenland, Iceland, and Norwegian seas (Nordic Seas). This process has been central to or part of previous scientific drilling expeditions in the northeast Atlantic region, and the results strongly indicate that these connections played a significant role in causing, or amplifying, environmental changes during the Cenozoic through their influence on water mass circulation (Laughton, 1975; Miller and Tucholke, 1983; Jakobsson et al., 2007; Boyle et al., 2017; Coxall et al., 2018; Vahlenkamp et al., 2018). Current questions are focusing again on the role and timing of mantle upwelling beneath Iceland in dynamically supporting regional bathymetry and the depth of oceanic gateways that control the strength of deep-water flow over geologic timescales (Miller and Tucholke, 1983; Poore et al., 2006; Parnell-Turner et al., 2014; Stärz et al., 2017), yet existing records are insufficient to move forward. The recovery of early Cenozoic sediments overlying Palaeocene volcanics on the Vøring Plateau, which are captured impressively in seismic profiles, will provide improved constraints on the evolving oceanic environment of the Nordic seas, especially the transition from non-marine to marine facies. Moreover, we suggest drilling a specified core in the trough "Judd Fall Drift", situated in the Faroe Bank Channel (one of the deep intersections of the Greenland–Scotland Ridge) (850 m water depth; Hohbein et al., 2012). Judd Fall Drift contains a thick sedimentary section (up to 900 m) of early middle Eocene to late Miocene (or early Pliocene) sediments and is interpreted from industry seismic evidence to contain a history of Nordic Seas overflow extending back to the middle Eocene (Hohbein et al., 2012). IODP coring of the sequence will be critical for testing this and competing hypothesis about the timing of Greenland–Scotland Ridge subsidence and associated onset of the formation of deep water in the North Atlantic in the early Cenozoic (Via and Thomas, 2006; Hohbein et al., 2012; Boyle et al., 2017; Coxall et al., 2018; Vahlenkamp et al., 2018). These palaeo-ocean gateway objectives will provide an older and more northerly perspective on the links between plume activity and ocean circulation to complement an existing IODP proposal focused on similar questions in the Neogene, i.e. IODP proposal 892 Full (Reykjanes Mantle Convection, Parnell-Turner et al., 2014).

5.2 Groundwater systems in breakup basalts and carbon storage

Submarine groundwater discharge is a global phenomenon contributing 3 %–30 % of the fresh water budget in various locations (Taniguchi et al., 2002; Post et al., 2013). In regions covered by glaciers and/or permafrost in the past, the circulation of meteoric water has been shown to relate to a large hydraulic head contrast as a result of the excess weight from glaciers (DeFoor et al., 2011). Signs of meteoric water circulation have been detected from the stable isotopes ($\delta^{18}O$ and δD) of water from ODP Leg 104 Sites 642 and 643 at the Vøring Plateau. Such observation is unexpected as these two drill sites are ca. 500 km from the shelf edge, where the maximum extent of glacier ice was during the Last Glacial Maximum (Patton et al., 2016). Similar signs of meteoric water were also observed along the continental shelf of the Norwegian margin (Egeberg and Aagaard, 1989) and more recently documented by Hong et al. (2019) from the Lofoten-Vesterålen continental slope (∼ 800 m water depth and ca. 100 km from the Lofoten Archipelago). Similar groundwater anomalies were also documented ca. 100 km southeast of the Greenland shelf (DeFoor et al., 2011).

The presence of meteoric water from the Norwegian and Greenland margins may be associated with the thick basaltic formation as a result of the breakup volcanism in the North Atlantic Ocean. Large-scale basaltic formations serve as quality aquifers at many places around the world. For example, the Columbia River Basalt Group from the western USA, one of the large igneous provinces, is a 163 687 km^2 aquifer that supplies fresh water to three states (Vaccaro, 1999). In addition to the potential for storing fresh water, basaltic formations are also good candidates for permanent CO_2 sequestration. Alteration of basaltic rocks can release calcium ions, which are one of the most essential ingredients for carbonate mineral formation. By injecting solutions into the basaltic formations, the dissolved CO_2 can be sequestrated in the formation as carbonate minerals. For example, the investigation of fluid geochemistry around Hekla, Iceland, has shown that the dissolution of basaltic materials can stimulate carbonate mineral precipitation and the drawdown of inorganic carbon content in the solution (Flaathen et al., 2009).

The observations of meteoric water and high dissolved calcium concentrations from the bottom of ODP Sites 642 and 643 have shown that the Vøring Plateau is an ideal place to study the circulation of fresh water within such a large basaltic formation and to assess its potential for CO_2 sequestration. However, what was not answered from the early studies is the origin of the meteoric water and the trigger(s) for such large-scale circulation. Furthermore, this will have repercussions on the role of meteoric-water circulation and water–rock interactions on carbon cycling and deep microbial ecosystems. The dating of the water samples from the borehole with tracers such as ^{14}C, ^{36}Cl, and $^{234}U/^{238}U$ (IAEA, 2013) and a systematic analysis of fluid geochemistry (Inagaki et al., 2015) will shed light on some of these questions.

6 Relationship to the IODP Science Plan for 2013–2023 and beyond

The breakup of the continents is a fundamental component of the plate tectonic cycle and major episodes of the agglomeration of crustal blocks into supercontinents and their subsequent rifting, and the formation of new oceans has punctuated Earth's evolution since the Archean. Rifting episodes result in major changes in the surficial conditions of our planet impacting Earth's atmosphere, climate, ocean circulation and chemistry, and life on land and in the oceans. Some of these events have resulted in the development of the major energy resources that have powered the world's economies for the past century. Consequently, the mechanisms and consequences of continental breakup and the nature of the still poorly defined transitions from continents to oceanic crust have been important targets for scientific ocean drilling since its inception in the Deep Sea Drilling Project 50 years ago.

The current phase of ocean drilling, the International Ocean Discovery Program, is guided by the community-derived science plan *Illuminating Earth's past, present, and future: exploring the Earth under the sea* (IODP Science Plan for 2013–2023). This document comprises 14 challenges within four major themes:

- "Climate and ocean change: reading the past, informing the future";
- "Biosphere frontiers: deep life and environmental forcing of evolution";
- "Earth connections: deep processes and their impact on Earth's surface environment"; and
- "Earth in motion: processes and hazards on human time scales".

A number of the challenges can be directly or indirectly related to the magmatic and tectonic processes occurring during continental rifting and the formation of passive margins. These include aspects of the composition, structure, and dynamics of Earth's upper mantle (Challenge 8), how seafloor spreading and mantle melting links to ocean crustal architecture (Challenge 9), and the chemical exchanges between the oceanic crust and seawater (Challenge 10). Continental breakup, whether accompanied by large-scale magmatism or principally tectonic, may have major impacts on global chemical cycles and the elemental and isotopic composition of seawater, but to date these effects remain poorly quantified for either volcanic or non-volcanic margins. Passive margins host major potential hazards from submarine landslides and resulting tsunamis (Challenge 12), offer possibilities for the industrial-scale storage of carbon dioxide (Challenge 13), and the loci for the flow of sub-seafloor fluids and consequent tectonic, thermal, and biogeochemical processes (Challenge 14). Although the climatic drivers and effects of magmatism and igneous sill intrusion on the Norwegian margin remain debated (see Sect. 3.3), the temporal coincidence of magmatism, northeast Atlantic breakup, and the major, geologically short-lived, carbon isotopic excursion of the PETM indicate that the sedimentary sequences bordering the northeast Atlantic margins are compelling targets to test models of sedimentary or igneous gas release, gas hydrate de-stabilisation, or thermogenic methane production during contact metamorphism. Direct, sub-seafloor observations of purported gas escape structures may be of direct relevance to anthropogenic-scale industrial carbon dioxide storage. These geological records could directly address ongoing scientific debates regarding the Earth's response to elevated atmospheric pCO_2 (Challenge 1) and other greenhouse gases, in particular methane, and the resilience of the oceans to chemical perturbations (Challenge 4). The science plan also includes a number of cross-cutting topics, a number of which can be partly addressed by a campaign of expeditions to the northeast Atlantic region, including hydrocarbon and other resources needed for the 21st century, the calibration of climate models through core observations and analyses, and serpentinisation, which is a major process on some rifted margins.

7 Conclusions

The North Atlantic Igneous Province is as thrilling a drilling target as ever. During the MagellanPlus Workshop an impressive amount of new data and ideas were presented. They showed that since the last drilling campaign in 1996 science has moved on, and new industry data do reveal drilling targets that would allow for testing two sets of hypotheses that had not been around for consideration when the last ODP drilling campaign took place. New IODP and ICDP campaigns would lead to a fundamental understanding of the processes that lead to large-scale breakup volcanism and to a better understanding of the consequences that breakup volcanism may have for climate evolution.

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Data availability. This contribution is based on previously published data (see references throughout the paper). Seismic data from TGS shown in Fig. 5 were used for illustrative purposes. These data have been uploaded for the safety assessment of the IODP proposal, but they are not publicly available.

Author contributions. CB, SP, and DT organised the workshop. SP, MTJ, and JIF compiled the industry seismic data. TT and JIF summarised the tectonic evolution; RH summarised the melt production; DAJ summarised the volcanic expressions; CT and JF summarised the climate implications; HC summarised the palaeoceanographic setting; and WLH and CB summarised the groundwater system. All authors contributed to the paper.

Competing interests. The authors declare that they have no conflict of interest.

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IODP beyond 2023

The International Ocean Discovery Program (IODP) has successfully entered its second phase of drilling, with the current IODP Science Plan scheduled to conclude in 2023. Central to the IODP endeavours in this phase is the multi-drilling platform approach to be able to drill in a wide range of environments. Many geoscientists from IODP member nations will have the unique opportunity to experience the sense of scientific discovery through sailing on one of the drilling platforms.

How about IODP beyond 2023? One of the IODP Forum consensus items (September 2018; Chair Jamie Austin) was visionary: "Multiple planning efforts underway to continue scientific ocean drilling beyond 2023 will eventually require coordination, both to reconsider the extant decadal Science Plan and to evaluate the envisioned mix of drilling platform capabilities, that will be necessary to respond to the expected continued flow of high-quality proposals. The Forum, or its successor, should play an important role in this."

The above Forum consensus has inspired the international scientific community to work on the first step of a post-2023 programme: the whirlwind of writing a new Science Plan. Several international workshops were organized this year—in Yokohama, Vienna, Canberra, Denver, and Shanghai—to discuss scientific priorities and possibilities for post-2023. Early- and mid-career scientists played prominent roles during all of these workshops, with the Canberra workshop setting aside a special session for early career researchers alone. An international working group of IODP scientists, representing all IODP nations and consortia, then met in New York in July to summarize and integrate results of the workshops and to form the skeleton of a very ambitious Science Plan for post-2023, with a timeframe of having the final product available by June 2020.

In September 2019, the Forum delegates had the opportunity to discuss, scrutinize, and alter where necessary the proposed skeleton of the new Science Plan during a very well-attended meeting in Osaka, Japan. The Forum delegates were very impressed with the Plan's progress and enthusiastically endorsed its development while suggesting it be renamed a "Science Framework", which better expresses the IODP community's long-range vision for taking scientific ocean drilling into the mid-21st century.

The Forum delegates thank the leaders and members of the New York working group for their hard work in developing this Science Framework for post-2023 and applaud the speedy formation of the writing and editing teams. We are looking forward to the final product in mid-2020, as it is necessary for long-range deliberation on the structure of a post-2023 scientific ocean drilling programme. The Forum delegates also recognize that the concept and design of the current IODP structure has proved highly successful and provides a powerful possible model to take forward into the next phase of scientific ocean drilling post-2023. There will be challenges, but these can and will be overcome through international collaboration among all member countries.

The Forum applauds the efforts of IODP and ICDP to streamline and simplify the Amphibious Drilling Proposal (Land to Sea Proposal) review process. This should be implemented as soon as possible in the current programmes of IODP and ICDP. For now, few details need to be worked out in the coming months. This simplification of the review process coordinated by IODP and ICDP supports scientific drilling endeavours along transects from land to shallow waters that cross-cut multiple disciplines, requiring interdisciplinary efforts to address specific science questions and specific societal challenges. IODP and ICDP are enthusiastic about working closely together implementing land to sea proposals. The land to sea drilling efforts will be specifically mentioned in the appropriate chapters of the new IODP Science Framework and the new ICDP Science Plan, both to be published in 2020.

Finally, on behalf of the Forum delegates, I would like to thank the organizers and participants in the many planning workshops that were held earlier this year. Their hard work has positioned scientific ocean drilling to flourish for many years to come.

Sincerely,

Dick Kroon
Chair, IODP Forum

ECORD Research Grants 2020 for Early Career Scientists

CALL FOR APPLICATIONS
DEADLINE: 31 January 2020

The European Consortium for Ocean Research Drilling (ECORD) is sponsoring merit-based awards for outstanding young scientists to conduct innovative research related to the International Ocean Discovery Program. The research may be directed toward the objectives of completed DSDP/ODP/IODP expeditions and should utilize available core material and/or data from expeditions. The ECORD Grants will cover travel and laboratory expenses or other approved costs related to the study.

More information: https://www.ecord.org/education/research-grant/

Training and Education

ECORD SUMMER SCHOOLS 2020

A major goal of ECORD is to train the next generation of scientists from member countries and promote IODP-motivated science. Several summer schools are sponsored every year by ECORD to further foster the education of young scientists in marine-related sciences and to train a new generation to participate in future ocean drilling expeditions. The ECORD Summer Schools in 2020 will be:

• ECORD Summer School 2020: Downhole Logging for IODP Science. 4-10 July 2020, Leicester, UK

• ECORD Summer School Bremen: Sea level, climate variability and coral reefs. September 2020, Bremen, Germany

• URBINO Summer School: Title and Place TBD

More information including call for scholarships will be posted here: https://www.ecord.org/education/summer-schools/

Innovative Exploration Drilling and Data Acquisition (I-EDDA) Research School

Innovative Exploration Drilling and Data Acquisition (I-EDDA) is a network of infrastructures funded by EIT Raw Materials (European Institute of Innovation & Technology). I-EDDA brings together drilling engineers and geoscientists in order to develop new field measurement technologies and drilling methods. Field testing of innovative downhole, core, and sampling analyses are combined with environmental studies and novel boring technology in order to advance the state of the art of integrated data analysis. This will serve to improve exploration methods as drilled boreholes will have greater value, as the data get integrated into the interpretation chain. There will be a need for fewer boreholes.
The I-EDDA Research School (I-EDDA-RS) consist of a series of different courses for PhD and MSc students, which focuses on themes of technologies and entrepreneurship in mineral exploration. Topics addressed by I-EDDA-RS include scientific methods applied to deep mineral explorations, exploration engineering, and the life cycle of exploration data. The first courses will take place in spring 2020. Scholars in scientific drilling are invited to apply (https://www.iedda.eu/material/I-EDDA-RS.pdf) from January 1, 2020 on.

Schedules

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

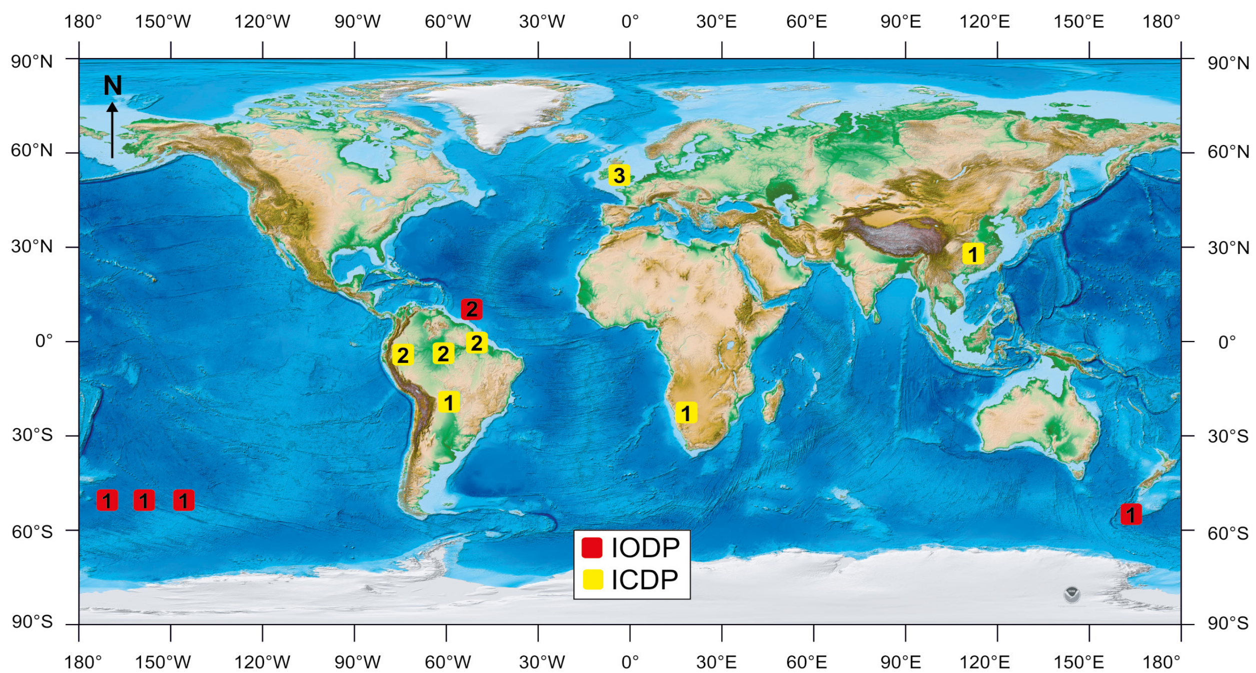
USIO operations	Platform	Dates	Port of origin
1 Exp. 378: South Pacific Paleogene Climate	JOIDES Resolution	Jan 3–Mar 4, 2020	Fiji
2 Exp 387: Amazon Continental Margin	JOIDES Resolution	Apr 26–June 26, 2020	Recife

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

ICDP project	Drilling dates	Location
1 GRIND	June 2019–June 2020	Namibia, Brazil, China
2 Trans-Amazon	April–December 2020	Brazil (multiple locations)
3 JET	March 2020–June 2020	Cheshire Basin, UK

Locations

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



Data Center, NOAA. doi:10.7289/V5C8276M).