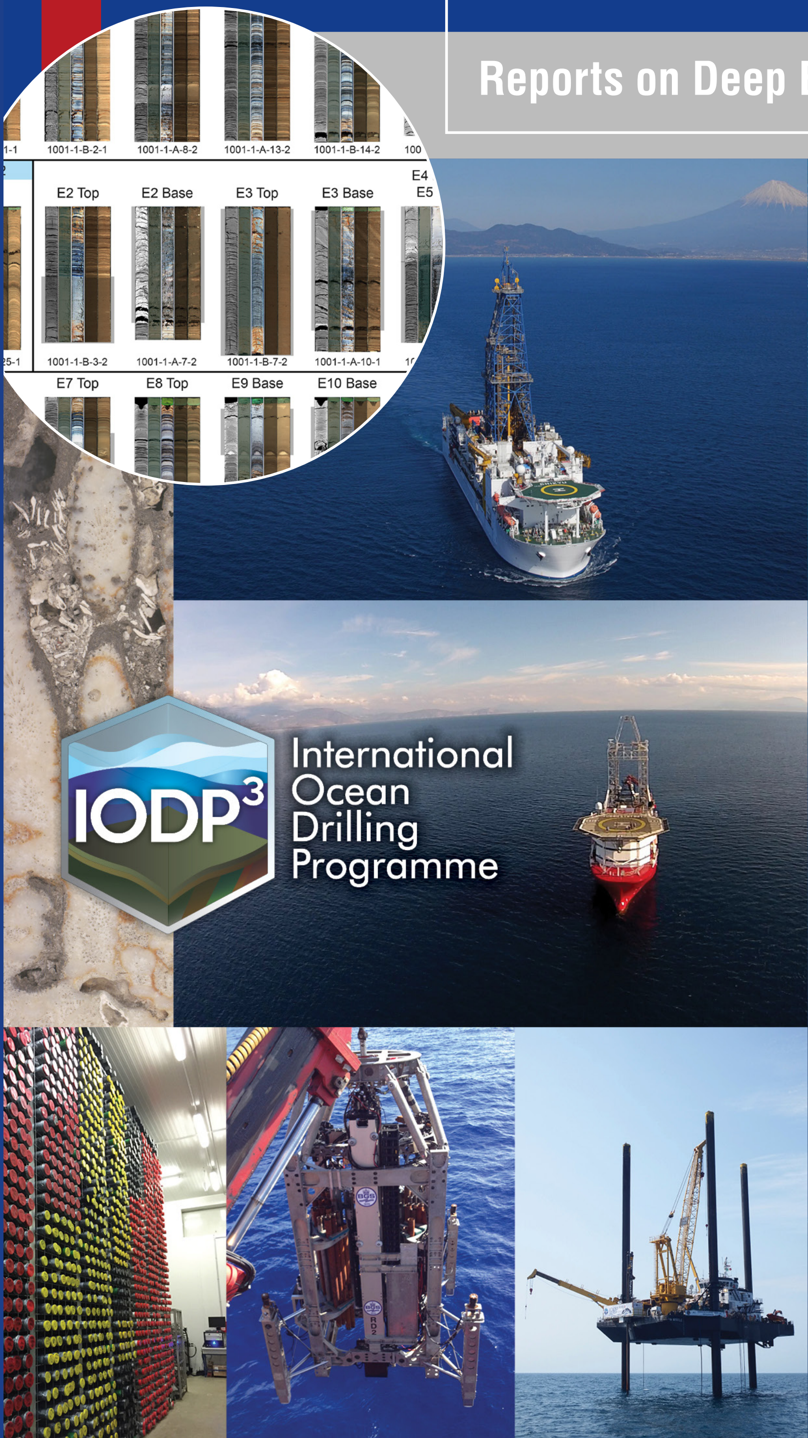
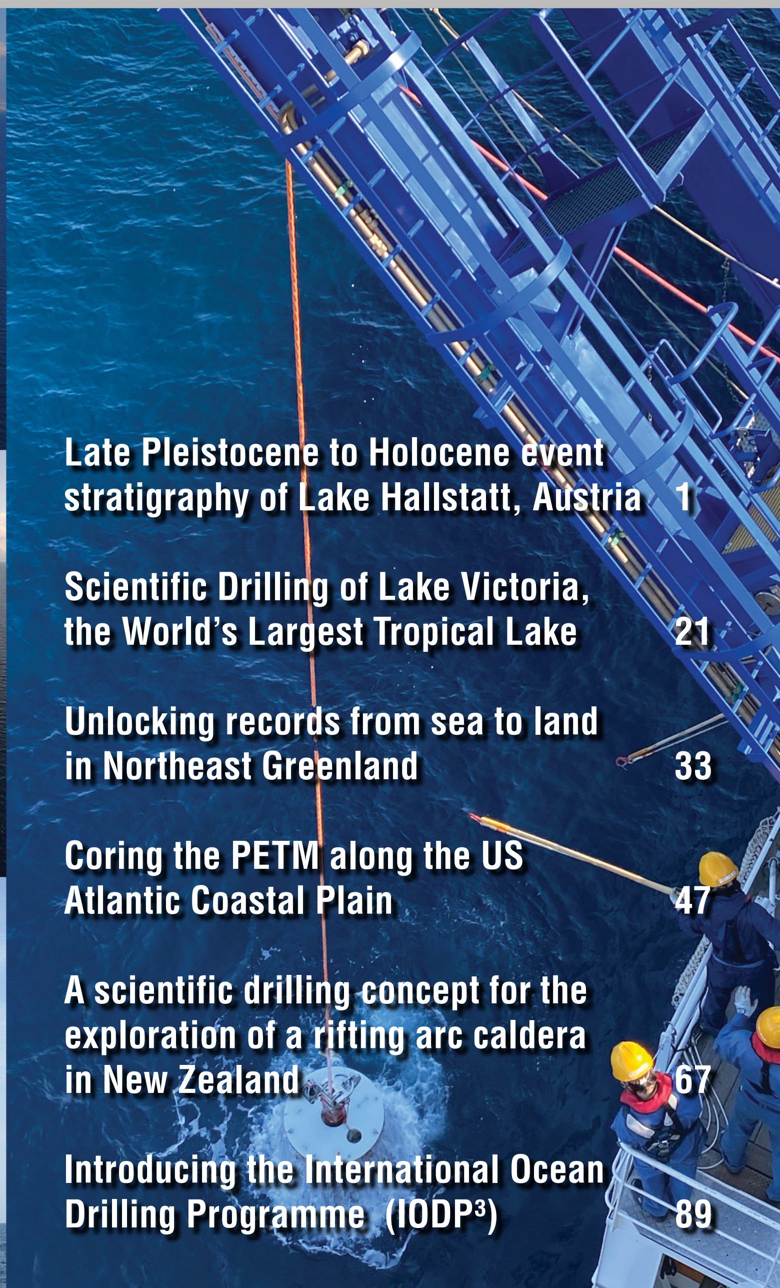
ISSN 1816-8957

No. 33, April 2024

Scientific Drilling

Reports on Deep Earth Sampling and Monitoring





Late Pleistocene to Holocene event stratigraphy of Lake Hallstatt, Austria 1

Scientific Drilling of Lake Victoria, the World's Largest Tropical Lake 21

Unlocking records from sea to land in Northeast Greenland 33

Coring the PETM along the US Atlantic Coastal Plain 47

A scientific drilling concept for the exploration of a rifting arc caldera in New Zealand 67

Introducing the International Ocean Drilling Programme (IODP³) 89

The open-access ICDP and IODP journal • www.scientific-drilling.net

Editorial preface

Dear reader,

Sediments archiving continuous and datable past changes in Earth system are key to improving our mechanistic understanding of complex interplays. This issue of Scientific Drilling provides insights into a couple of new initiatives on these topics with one Science Report and three Workshop Reports.

In the context of the ongoing discussion about the Anthropocene as a new geological epoch and its beginning, it is worth noting that the impact of humans on the environment can be recognized throughout the Holocene. One vivid example is the Bronze Age salt mining in the European Alps around Lake Hallstatt causing a strong influx on sediments in the nearby lake. A drilling campaign with a special coring system resulted in the recovery of a high-resolution, multi-proxy and multi-disciplinary-based analysis of the Late Pleistocene to Holocene sedimentary succession (**p. 1**).

Upper Pleistocene deposits of Lake Victoria address questions about Quaternary landscapes and ecosystems in eastern Africa (**p. 21**). An interplay of geological, paleontological, climatological, and evolutionary biological investigations is designed to develop conservation and management strategies for regional responses to current and future changes in the environment in equatorial Africa. A better understanding of the long-term stability of the Greenland ice sheet is key for anticipating future climate and sea-level developments. The past waxing and waning of this ice sheet are documented offshore from the island's northeastern continental margin, whose sediments are targets of future mission-specific ocean drilling campaigns (**p. 33**). An outstanding analog to modern atmosphere temperature rise is the Paelocene/Eocene Thermal Maximum, PETM. Thick sections of PETM strata are deposited along the US mid-Atlantic coastal plain. Prospects for sampling and studying these deposits were the goal of the workshop on "Paleogene Earth Disturbances in the U.S. Atlantic Coastal Plain", reported on **p. 47**. Finally, the report (**p. 67**) on Connections Among Life, geo-Dynamics and Eruptions in a Rifting Arc (CALDERA) sheds light on the importance of hazards and resources in volcanic caldera systems. The Okataina Volcanic Centre in New Zealand is a prime example for investigating the most critical questions through subsurface observations by scientific drilling.

The end of the International Ocean Discovery Program (IODP) on 30 September 2024 will mark major changes in the organization of international scientific ocean drilling. ECORD and Japan have agreed to build a new joint scientific ocean drilling program, whose objectives and organizational structure are laid out in Program Development report (**p. 89**).

With this issue, the editorial board of Scientific Drilling is changing as our editor-in-chief Uli Harms will be leaving the panel after long service as co-founder and member of the editorial board. Managing editor Thomas Wiersberg will succeed him in this role. At the same time, we welcome Hendrik Vogel from Bern University in Switzerland as a new board member who will be bringing exciting new expertise to the journal with his background in sedimentary geochemistry.

With best regards,
the editors of *Scientific Drilling*

Ulrich Harms, Thomas Wiersberg, Nadine Hallmann, 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.

Editorial board

Ulrich Harms (editor in chief),
Thomas Wiersberg, Nadine Hallmann,
Will Sager, and Tomoaki Morishita

sd-editors-in-chief@mailinglists.copernicus.org

Additional information

Copernicus Publications
The Innovative Open Access Publisher

ISSN 1816-8957 | eISSN 1816-3459

Copernicus Publications
Bahnhofsallee 1e
37081 Göttingen
Germany
Phone: +49 551 90 03 39 0
Fax: +49 551 90 03 39 70

editorial@copernicus.org
production@copernicus.org

https://publications.copernicus.org

View the online library or learn more about Scientific Drilling on:
www.scientific-drilling.net

Cover figure: The International Ocean Drilling Programme (IODP[3]) (p. 89).
Insert 1: Compilation of drilling core images from L. Hallstatt (p. 1).
Insert 2: Electron backscatter images of spherules from Wilson Lake and Millville (p. 47).

Contents

Science Reports

1 **Late Pleistocene to Holocene event stratigraphy of Lake Hallstatt (Salzkammergut, Austria): revealed by the Hipercorig drilling system and borehole logging**
M. Ortler et al.

Workshop Reports

21 ICDP workshop on the Lake Victoria Drilling Project (LVDP): scientific drilling of the world's largest tropical lake

33 NorthGreen: unlocking records from sea to land in Northeast Greenland

47 Paleogene Earth perturbations in the US Atlantic Coastal Plain (PEP-US): coring transects of hyperthermals to understand past carbon injections and ecosystem responses

67 CALDERA: a scientific drilling concept to unravel Connections Among Life, geo-Dynamics and Eruptions in a Rifting Arc caldera, Okataina Volcanic Centre, Aotearoa New Zealand

Program Developments

89 The International Ocean Drilling Programme (IODP^3)

Sci. Dril., 33, 1–19, 2024
https://doi.org/10.5194/sd-33-1-2024
© Author(s) 2024. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

Late Pleistocene to Holocene event stratigraphy of Lake Hallstatt (Salzkammergut, Austria): revealed by the Hipercorig drilling system and borehole logging

Marcel Ortler[1], Achim Brauer[2,3], Stefano C. Fabbri[4,5,6], Jean Nicolas Haas[7], Irka Hajdas[8], Kerstin Kowarik[9], Jochem Kueck[10], Hans Reschreiter[11], and Michael Strasser[1]

[1]Department of Geology, University of Innsbruck, Innsbruck, Austria
[2]Institute of Geosciences, University Potsdam, Potsdam, Germany
[3]Section Climate Dynamics and Landscape Evolution, GFZ German Research Centre for Geosciences, Potsdam, Germany
[4]Institute of Geological Sciences, University of Bern, Bern, Switzerland
[5]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[6]Institut des sciences de la mer de Rimouski (ISMER), Université du Québec à Rimouski, Rimouski, Canada
[7]Department of Botany, University of Innsbruck, Innsbruck, Austria
[8]Laboratory of Ion Beam Physics, ETH Zürich, Zurich, Switzerland
[9]Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria
[10]Geomechanics and Scientific Drilling, GFZ German Research Centre for Geosciences, Potsdam, Germany
[11]Prehistoric Department, Natural History Museum Vienna, Vienna, Austria

Correspondence: Marcel Ortler (marcel-luciano.ortler@uibk.ac.at)

Received: 24 May 2023 – Revised: 8 September 2023 – Accepted: 23 October 2023 – Published: 2 April 2024

Abstract. The Hipercorig Hallstatt History (H^3) project aims to unravel the entire Late Glacial to Holocene sedimentary succession recording past climate, environment, natural hazard impacts, human–environment interactions, and prehistoric mining history. We successfully cored 51 m of the sedimentary succession of Lake Hallstatt, revealing a high-resolution Late Pleistocene to Holocene sediment record, overcoming the previous coring limit of 15.63 m (dated to ∼ 2.3 ka cal BP). The novel drilling platform Hipercorig allows the recovery of undisturbed long cores and the acquisition of borehole logging data of deep lakes. The sedimentary record is spliced to a composite core profile, and for the first time borehole logging data are linked to a core–log seismic correlation of an intra-mountainous lake of the Eastern Alps. The recovered sequence consists of two major lithostratigraphic units: (i) Unit 1 (Holocene, 0–41.7 m below lake floor) with 10 (up to 5.1 m thick) instantaneous deposits and (ii) Unit 2 (Late Pleistocene, > 41.7 m below lake floor). The Late Pleistocene sediments comprise the Younger Dryas and the deepest recovered sediments likely date back to the Allerød interstadial. Within the Holocene, six different periods are observed in the core and borehole logging data, showing distinct physical property fluctuations and an overall increase in sedimentation rate upcore. Lake Hallstatt provides a unique prehistoric archive, being located within the UNESCO World Heritage area Hallstatt–Dachstein/Salzkammergut, a region with a rich history of human salt mining dating back to 3400 cal BP (Middle/Late Bronze Age) and one of the oldest documented cultural landscapes worldwide.

1 Introduction

The aim of deep drilling in lakes is to recover a high-resolution sedimentary stratigraphy to study past climate, environment, natural hazard impacts, and human–environment interactions. Such lakes can help to improve our understanding on a local, regional, and sometimes even global scale, covering parts of the Quaternary (Litt et al., 2012; Wagner et al., 2019) and beyond (Brigham-Grette et al., 2013). Borehole logging data can help to reconstruct the lithostratigraphy, estimate the clay content, bridge sediment core gaps for improved core–log depth correlation, and help to correct for core compaction and expansion (Baumgarten et al., 2014, 2015; Jutzeler et al., 2014). The Hipercorig, a sediment coring system, was developed to overcome the financial and logistical burden of the usual long-core drilling campaigns. It simplifies the coring technique to a degree that the recovery of 100 m long sediment cores from deep lakes or shallow marine environments is much more effective (Harms et al., 2020). So far, two lakes were cored during an initial testing phase of the new system: Lake Constance (Germany–Austria–Switzerland) with a water depth of up to 204 m and 87 % core recovery (Harms et al., 2020; Schaller et al., 2022) and Mondsee (Austria) with a coring depth of 63 m, accessing sediments dating back to ∼ 18.4 ka cal BP (Harms et al., 2020).

Mountainous regions are among the most sensitive to climate change and natural hazard processes (Adler et al., 2022) of different causes (e.g., meteorological, hydrological, and/or seismic hazards) and potentially cascading effects. Such hazards can range from local-scale events (e.g., debris flows, rockfalls, or avalanches; e.g., Kiefer et al., 2021; Knapp et al., 2018) to large-scale regional events (e.g., earthquakes, droughts, or floods; e.g., Oswald et al., 2021; Swierczynski et al., 2013) threatening human lives and infrastructure. Even though flood-rich periods in central Europe coincided with relatively cold periods in the past 9000 years (e.g., Blöschl et al., 2020; Wilhelm et al., 2022), it is expected that extreme precipitation in mountainous regions will increase in the currently warming climate in all IPCC scenarios (Arias et al., 2021), with likely cascading effects of, e.g., landslides or floods. A clear commitment to assess extreme events is vital to reduce the vulnerability and exposure of human societies to such hazards. To this end, high-quality observational data over long timescales are needed, to evaluate recurrence rates, patterns, and magnitudes of potential future extreme events with statistical relevance (e.g., Moernaut, 2020; Sabatier et al., 2022). However, short historical and even shorter instrumental records limit our knowledge of natural hazard processes, leading to significant uncertainties in risk assessment (Costanza et al., 2007; Stein et al., 2012), potentially underestimating extreme events with low-probability but high-impact outcomes. Therefore, studying prehistoric events using geological records is needed (i) to reconstruct the past occurrence of meteorological, hydrological, and seismological hazards and their anthropogenic impacts, as well as their complex interactions, and (ii) to gain a better understanding of magnitude–frequency relations of natural hazards to reduce epistemic uncertainties in their assessment. The intra-mountainous UNESCO area Dachstein/Salzkammergut (Austria) is an exceptionally well-suited study area for investigating natural hazards and human–environmental interactions, due to a long history of human impact and settlement (Reschreiter and Kowarik, 2019) and documented historic and prehistoric evidence for human–environmental interactions (Barsch et al., 2023; Festi et al., 2021; Grabner et al., 2021; Knierzinger et al., 2021; Reschreiter and Kowarik, 2019). Previous short-core and conventional lake coring studies have documented the last ∼ 2.3 kyr cal BP (at 15.63 m) of Lake Hallstatt's sedimentary infill (Lauterbach et al., 2023; Strasser et al., 2020).

The Hipercorig Hallstatt History (H^3) project overcomes the previous coring limitations through the novel Hipercorig platform (Harms et al., 2020) and accesses the deeper high-resolution lacustrine archive of Lake Hallstatt allowing state-of-the-art multiproxy-based research. Here, we present the first major event stratigraphy of an intra-mountainous, high-resolution lake record of the Eastern Alps, based on the combination of seismic airgun data, borehole, and core logging. The first-time use of borehole logging data on the Hipercorig system enables us to better understand and link the cored sedimentary evolution of Lake Hallstatt to the seismic data and its seismic stratigraphy.

2 Regional setting and previous studies

Lake Hallstatt (47°34′25″ N, 13°39′35″ E; 508 m above sea level, area of 8.55 km^2, ∼ 7.5 km long, up to 1.4 km wide, lake volume ∼ 558×10^6 m^3, maximum water depth 125 m, Fig. 1) is a former glacial, fjord-like, intra-mountainous lake, classified as oligotrophic, with holomictic–dimictic mixing with infrequent meromictic phases (Beiwl and Mühlmann, 2008; Ficker et al., 2011). The lake is located in the UNESCO World Heritage region Hallstatt–Dachstein/Salzkammergut, Austria. The area is situated in the Northern Calcareous Alps, with steep limestone mountains surrounding it and the still glaciated Dachstein Massif to the south and the Totes Gebirge in the northeast within the upstream catchment area.

Today, the north–south-stretching lake can be subdivided into two sub-basins: (i) a shallower northern basin (∼ 45 m deep) and (ii) a deeper southern basin (∼ 125 m deep; Strasser et al., 2020). The formation of the overdeepened lake basin occurred through repeated glacial erosion. The last glacial cycle ended ∼ 17 ka cal BP with the retreat of the Traun Glacier (Van Husen, 1977, 1997, 2011). The primary clastic carbonate influx mostly comprises the eroded surrounding Triassic limestones of the Dachstein Formation (Mandl et al., 2012).

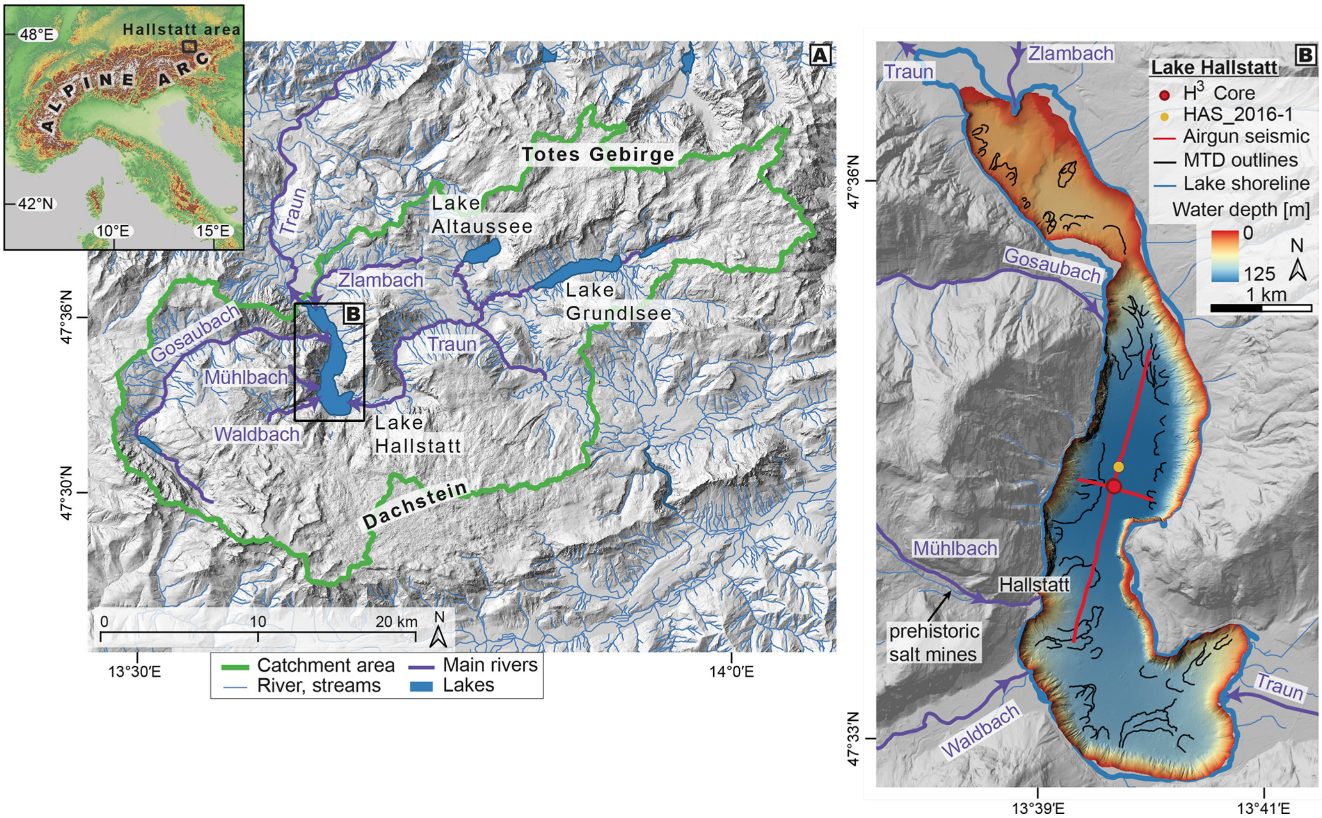


Figure 1. **(a)** Location of Lake Hallstatt (Salzkammergut, Austria) in the Alpine Arc (inset) and overview map of the Lake Hallstatt region north of the Dachstein Massif and southwest of the Totes Gebirge, with its catchment area outlined on a shaded relief map. The digital elevation models were taken from Copernicus Land Monitoring Services (European Digital Elevation Model (EU-DEM), version 1.1) and http://data.gv.at (last access: 12 January 2021) (http://geoland.at, last access: 12 January 2021, Umweltbundesamt GmbH, Land Steiermark, Land Oberösterreich), including catchment area and water network. **(b)** Lake Hallstatt overview map, with the N–S and W–E seismic airgun transects and the H^3 coring locations (red dot), including the previous HAS_2016-1 core site (yellow dot) of Lauterbach et al. (2023). Bathymetry data and mass-transport deposit (MTD) outlines following Strasser et al. (2020).

The catchment area of Lake Hallstatt covers 646 km^2, with the Traun River in the SE as the main river inflow contributing 53 % of total inflow and ∼ 50 % of the total catchment area. The Traun inflow has a mean annual discharge (1970–2006) of 20.7 $m^3\,s^{-1}$ (Ficker et al., 2011). Other larger tributaries are the Gosaubach in the northwest, the Waldbach in the southwest flowing into the southern basin, and smaller tributaries such as the Großer Zlambach in the north flowing into the northern basin and the Mühlbach at the town of Hallstatt, draining the high valley of the Hallstatt salt mine area. The mining area is located geologically within the upper Permian to Lower Triassic Haselgebirge Formation (e.g., Fernández et al., 2021; Schorn and Neubauer, 2014). Evidence for large-scale underground rock salt mining dates back at least to 3400 cal BP (Grabner et al., 2019). The salt-enriched Haselgebirge Formation is also present around Lake Altaussee and Grundlsee upstream of Lake Hallstatt, as well as around Bad Ischl and Ebensee.

The history of this Alpine landscape is well-documented through archeological data and written records indicating that this region was settled more or less continuously since the Bronze Age at the latest (Festi et al., 2021; Reschreiter and Kowarik, 2019). Due to the economic importance of this region a substantial record of written sources exists and provides insights into the last 400 years, including mentioning catastrophic events such as mass movements, heavy precipitation with debris flows, shoreline collapses, and earthquakes (e.g., Melzner, 2017; Reschreiter and Kowarik, 2019; Rohn et al., 2005; Urstöger, 2000).

On occasion, these sources also convey information on societal reaction to these geohazards, including information on early geoengineering in the catchments and river redirections (Pürstinger, 2017; Urstöger, 2000). Historical information from major floods of the Traun river contributed to a comprehensive European flood study also covering the last 500 years (Blöschl et al., 2020; Kiss, 2019; Rohr, 2006, 2007). Furthermore, long-term limnological monitoring data over the last century also document the effects of wastewater intrusions from salt mining, including the salt mine in Altaussee, on water column stratification in Lake Hallstatt (Ficker et al., 2011).

A previous study by Strasser et al. (2020) investigated the geomorphology and event stratigraphic record covering the last ∼130 years of Lake Hallstatt. They report an ultra-high-resolution sedimentary archive with (millimeter to sub-millimeter) laminated background sediment and sedimentation rates of 0.50 to 0.4 $cm\,yr^{-1}$. High-frequency hydroacoustic subsurface imaging was limited to 4–5 m of the sedimentary infill and revealed parallel and laterally continuous low- to medium-amplitude reflections. Several gravitational mass movements were identified, and event layers comprising turbidites and mass-transport deposits are correlated to specific floods in the 19th and 20th century and moderate earthquakes, respectively (Strasser et al., 2020). Furthermore, a study of Lauterbach et al. (2023) revealed, three large-scale mass movement event deposits: E1 – 84 ± 48 cal BP; E2 – 1058 ± 60 cal BP; E3 – 2313 ± 131 cal BP (Lauterbach et al., 2023). These were interbedded within the background sedimentation. Likely, the coarse character of the large-scale event deposit of E3 restricted the previous coring expedition to 15.63 m.

3 Methods

3.1 Site survey and site selection

Hipercorig drilling was planned to be in the depo-center of the southern basin near the previous coring location (HAS_2016-1, Fig. 1b) (Lauterbach et al., 2023). Previous coring in 2016 was abandoned at 15.63 m depth when reaching the upper part of E3, a major mass-transport deposit (MTD; Lauterbach et al., 2023). A single-channel seismic survey was conducted in March 2021, with the objective to locate the optimal site for drilling with a potentially more complete stratigraphic succession and thinner E3. A mini-airgun (Sercel Mini GI, 220 Hz center-frequency) was used, with a volume of 0.016 L (1 cubic inch), a pressure of 80 bar, and a shooting interval of 2 s in combination with a 12-element single-channel streamer (3 m active length). The theoretical vertical resolution is ∼1 m. The data were preprocessed (using (1) DC (direct current) Removal, (2) TAR (True Amplitude Recovery), (3) DC Removal, (4) BPF (bandpass filter) 30-90-2000-2500, (5) trace equalization, and (6) FX (frequency spatial distance)-Deconvolution and BPF 100-150-2000-2500) and applying another bandpass filter (100-150-1000-1500) in the IHS Markit Kingdom Suite 2022, which was also used for seismic interpretation. An acoustic velocity of 1500 $m\,s^{-1}$ was used for the conversion from two-way travel time (TWT) to depth. Due to the limitation of the single-chamber airgun system, a bubble pulse effect (typically at 25 ms, with 60 Hz) is noticeable on the seismic sections, creating artifacts below 25 ms TWT (∼22.5 m below lake floor, m b.l.f.) (Lankston, 2017), which hamper the interpretation (Fig. 2, green arrows). Based on the new seismic airgun data, the H^3 site was selected ∼200 m south of the HAS_2016-1 coring site.

3.2 Drilling campaign

Drilling at the H^3 site was carried out with the Hipercorig system at 125 m of water depth between April and June 2021 and operated by the UWITEC GmbH (Mondsee, Austria). The drilling platform is a combination of a hydraulic down-the-hole (DTH) hammer with an established UWITEC piston coring system. It is a very versatile mobile, modular barge system, with steel casings, a lake bottom ground plate, and other auxiliary equipment (Harms et al., 2020). Two holes with ∼8 m lateral offset (Table 1) were cored with a 1 m vertical offset, to allow a vertical overlap of both holes (core length: 2 m, core diameter: 90 mm). A total length of ∼91 m (hole A 40 m, hole B 51 m; Fig. 2) of sediment cores was retrieved.

Sediment cores were curated on site with the mobile Drilling Information System (mDIS; Behrends et al., 2020), kept in ice-cooled Styrofoam boxes on the platform, and moved daily to a cool salt mine tunnel at ∼8 °C for temporary storage (1–4 d). The sediment cores were then transported to the University of Innsbruck, where they were kept at 4 °C.

3.3 Downhole logging

At the last day of on-site operations, while recovering the casing from hole B, downhole logging was conducted using the International Continental Scientific Drilling Program (ICDP) memory-logging system (iMLS), a modular "logging while tripping" (LWT) system, in online mode for wireline measurements (Kück et al., 2021). The data acquisition was performed in wireline mode; i.e., the sondes were operated on a regular logging cable and winch, with the data being read out in real time at the surface. This was possible because the otherwise autonomously measuring iMLS memory sondes can also be run with a special wireline telemetry (Kück et al., 2021; see more details in Sect. S1 in the Supplement). The memory sonde string did the following: (i) memory spectrum gamma ray (mSGR) (1.2 m long) measured profiles of both the total natural gamma ray (GR) and the concentrations of U, K, and Th from the spectrum of the natural gamma radiation, and, mounted below, (ii) memory magnetic susceptibility (mMS) (1.4 m long) measured magnetic susceptibility and temperature. Both sondes have a nominal vertical resolution of 0.2 m. The mMS position below the mSGR in the sonde string results in a magnetic susceptibility (MS) profile being 1.4 m longer than that of the mSGR data. Once inside the casing pipes the sonde was lowered towards the bottom of the piston corer until the mMS sonde stuck out of the corer and the mSGR sonde mounted above remained inside the pipes. The mSGR can measure

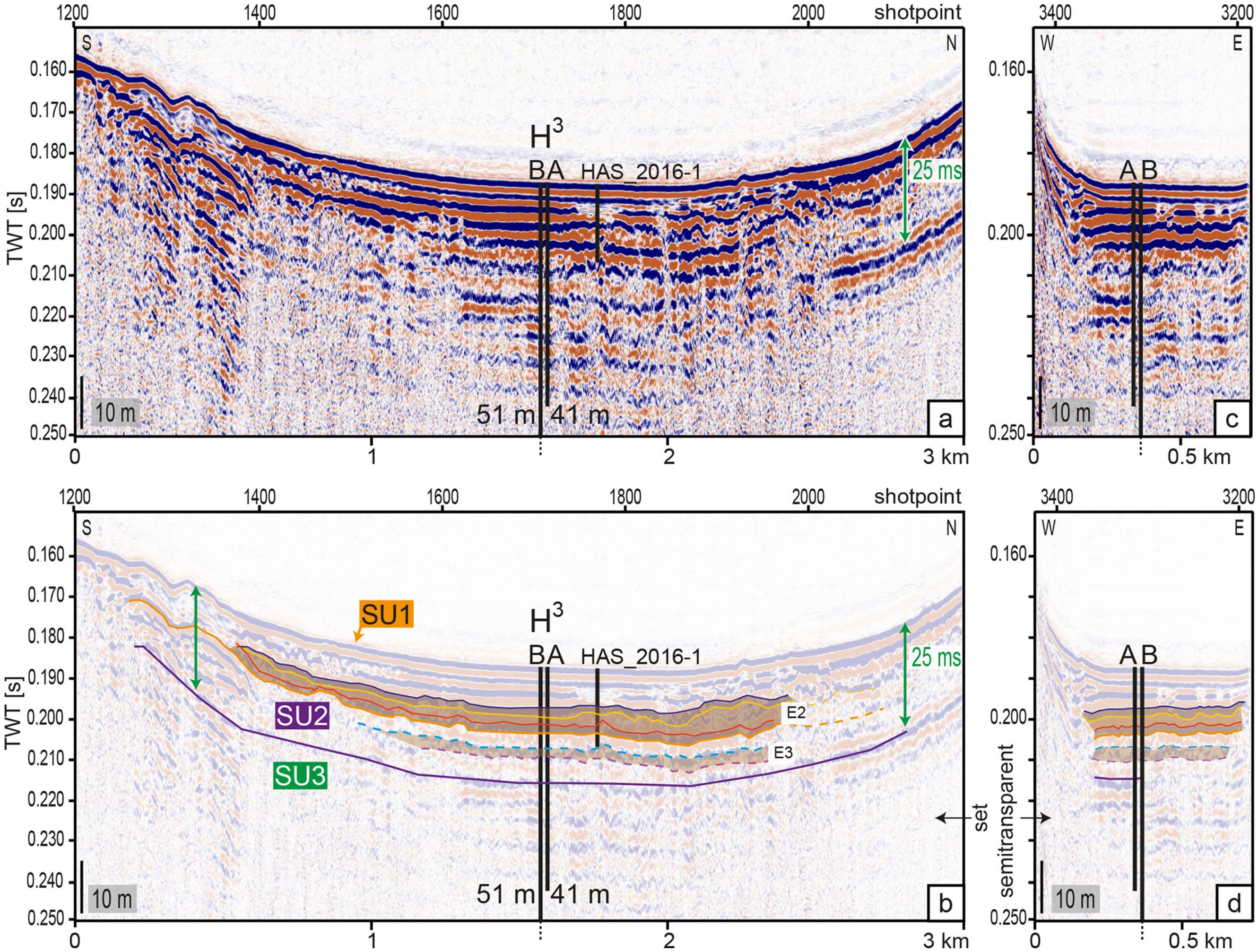


Figure 2. **(a)** Reflection seismic airgun profiles for Lake Hallstatt (Salzkammergut, Austria) from south to north revealing the upper ∼ 15 m of the sedimentary succession at the coring location H^3 (boreholes A and B) and a seismic window (SP 1270–1390) in the southern part near the alluvial fan of Hallstatt with ∼ 40 m penetration depth; the green arrow indicates bubble pulse reflection (25 ms). **(b)** Interpretation of profile shown in panel **(a)**. Dark blue, yellow, red, and orange horizons mark the different intervals within E2 showing different facies of E2: the upper interval (between dark blue and yellow) representing the turbidite deposit, the interval below (between yellow and red) representing the upper part of the mass-transport deposit (MTD), and the interval below that (red to orange) representing the lower, coarser part of the MTD; the deeper MTD E3 is indicated as a semi-transparent unit below, with dashed, light blue as the top and dashed light purple as the potential bottom; the purple line ∼ 145 m b.l.l. indicates the potential double pulse. **(c)** Reflection seismic airgun profiles from west to east showing the upper ∼ 15 m of the sedimentary succession and bubble pulse reflection (25 ms) as indicated in panel **(a)**. **(d)** Interpreted reflection seismic airgun profiles from west to east, as indicated in panel **(b)**. Abbreviations: SU – seismic unit; TWT – two-way travel time.

Table 1. Water depths and core recoveries for the Hipercorig Hallstatt History (H^3) drilling project at Lake Hallstatt (Salzkammergut, Austria). Abbreviations: m b.l.l., meters below lake level (in spring 2021); m b.l.f., meters below lake floor. Drilling hole B is located around 7–8 m SE of hole A.

Borehole	Coordinates		Water depth (m)	Top depth (m b.l.l.)	Top depth (m b.l.f.)	Total drilled length (m)	Core recovery (m)	Core recovery (%)
A	47.572998° N	13.659365° E	125	125	0	41	38.38	94
B	47.572955° N	13.659446° E	125	125	0	51	48.07	86

through the metal of a casing, but the mMS can only be measured in the open hole.

For the actual logging, both the sonde string and the casing pipe were pulled up as synchronously as possible, so that the mMS sonde would stay below the pipe. The synchronization happened manually by the logging winch operator and the rig operator. Since it was the first time this was attempted, the two pulling speeds were not always perfectly matched but varied slightly, causing the mMS sonde to briefly slip into the housing three times and lose the mMS measurement there. This prevented a continuous profile of the magnetic susceptibility. Despite these gaps in the mMS profile, the profile itself is consistent in depth throughout and serves as a depth reference. The logging depth scale is in meters below lake level (m b.l.l.); i.e., the depth reference is the lake surface at the barge. The lake floor is visible in the GR profile as a steep slope over about 1 m (124–125 m b.l.l.). It does not appear as a sharp edge because the GR sensor first sees the decreasing radiation when getting closer to the water and then continues to sense gamma radiation from the underlying sediments slightly above the lake floor. Further, it can be assumed that the lake floor does not show a sharp sediment–water interface but that sediments, swirled up by the coring process, probably cover the lake floor.

3.4 Core opening, non-destructive analyses, and core description

The whole-round cores were scanned using X-ray computed tomography (CT) with a voxel size of $0.2 \times 0.2 \times 0.3\,\text{mm}^3$ at the Medical University of Innsbruck (Austria) using a Siemens SOMATOM Definition AS. A Geotek Multi-Sensor Core Logger (MSCL) at the Austrian Core Facility (Department of Geology, University of Innsbruck) measured the whole-round cores with 0.5 cm resolution (bulk measurements: magnetic susceptibility, P-wave velocity, and γ density). After core splitting high optical images were obtained using a Smartcube Camera Image Scanner (SmartCIS; image scans of split core surface at 500 dpi resolution) and the COX Analytical Systems Itrax X-ray fluorescence core scanner (XRF-CS) (filtered and color-adjusted RGB images with up to $\sim 50\,\mu\text{m}$ optical resolution; Croudace et al., 2006). Visual core description and sediment classification follow Schnurrenberger et al. (2003). The identification of event deposits is based on general concepts after Sabatier et al. (2022), using mainly sedimentary structures and thickness to distinguish major event deposits from background sedimentation, without further trigger interpretation. Here we indicate event deposits with a minimum thickness of 0.3 m and sequentially apply the numbering introduced by Lauterbach et al. (2023) at site HAS_2016-1.

3.5 Stratigraphic correlation

The first-order composite profile was created to establish a continuous sediment sequence. For the construction of a common depth scale (composite depth scale), visual tie points (identification of coeval, laterally continuous features) were established for both H^3 drilling holes and the HAS_2016-1 composite core from Lauterbach et al. (2023). The visual tie points occur at different core depths below the lake floor (CLF-A) for each hole. The resulting core composite below the lake floor (CCLF-A) scale (meters composite depth – m c.d.) is based on the horizontal alignment of visual tie points and is equivalent to the old Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program meters' composite depth scale (IODP depth scales terminology, 2023). Where coring gaps occur at correlative depths or correlation between holes is non-conclusive, the floating composite section below is appended to the overlying section above (see more details in Sect. S2 and S2.1 and Tables S1, S2, and S3 and Fig. S1 as well as Ortler, 2023, for the visualization of the MSCL data using 15-point rolling Gaussian smoothing).

3.6 Core–log correlation

The core–log correlation was established through the correlation of a smoothed MSCL MS dataset (centered mean rolling average of 40 data points to match the MS borehole logging resolution of 0.2 m) and the MS data of the borehole logging (see detailed description in Sect. S7). The borehole logging MS data (measured in hole B) represents the in situ stratigraphy and was used to anchor the MSCL MS dataset, which was adjusted visually based on specific MS peaks and intervals of both datasets (see tie point table in Table S7). This allows us to better understand intervals of potential missing sediments (core gaps) and compaction/extension within our composite core.

3.7 Radiocarbon dating and age–depth modeling

From the two H^3 cores 24 accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates were performed on determined macro-remains from terrestrial plants below 18 m c.d. extracted by wet sieving of lake sediment samples using a mesh size of $> 125\,\mu\text{m}$ (Table 2). Small twigs from trees and shrubs were determined to taxon/species level by Werner H. Schoch (Laboratory for Ancient Wood Research, Switzerland) prior to dating. Core catcher samples were dated for an early age estimation directly after sediment coring but without detailed documentation.

Radiocarbon measurements were done at the Ion Beam Physics Laboratory of ETH Zürich, Switzerland, using the dedicated MICADAS system (Synal et al., 2007). Carbonates and humic acids were removed using an acid and base treatment as described by Hajdas (2008) in order to avoid potential contaminations. Single radiocarbon ages were calculated according to Stuiver and Polach (1977), were than calibrated

Table 2. AMS radiocarbon (^{14}C) dates were performed on macro-remains from terrestrial plants extracted from the sediments of Lake Hallstatt (Salzkammergut, Austria). All data were calibrated at ETH Zürich with OxCal 4.4.4 (Bronk Ramsey, 2009) and the atmospheric calibration curve IntCal20 (Reimer et al., 2020). CC represents core catcher material, which was pushed into mini cores up to 15 cm in length. Dates in italics are from event layers (omitted ^{14}C dates; see Fig. 4). Abbreviations: B – bark; BS – bud scale; CC – core catcher samples; ETH – Eidgenössische Technische Hochschule (Switzerland); FL – foliage leaf; L – leaf; Misp – microsporophyl; N – needle; n.d. – not determined; n.m. – not measured; P – part; Pe – periderm; SS – short shoot; St – stem; T – twig.

ETH lab code and dating method (g: graphite; GIS: gas ion source)	Core name & section depth (cm)	Composite depth (m)	Dated material and dry weight (mg)	$\delta^{13}C$ values (‰)	mg C	^{14}C age BP ± 1σ (uncal.)	Calibrated ^{14}C age ranges (cal BP)
121858 (g)	1001-1-A-10-2 (30)	18.67	1 *Abies alba* T (21)	−31.2	0.99	2470 ± 22	2425–2711
135231 (g)	1001-1-B-9-2 (73.5)	19.066	4 *Juniperus* N-P, 9 *Picea abies* N-P, 3 Bryophyta St (3.1)	−29.8	0.54	2708 ± 25	2759–2852
121857 (g)	*1001-1-B-10-1 (67.5)*	*22.19*	*5 Abies alba N-P, 1 Picea abies N-P, 1 Larix decidua N-P (4)*	*–29*	*0.99*	*3283 ± 22*	*3453–3562*
121860 (g)	1001-1-B-10-2 (47)	22.94	1 *Fagus sylvatica* T-P (37.6)	−30.8	0.99	3230 ± 22	3390–3481
135233 (g)	1001-1-A-12-2 (44.5)	24.111	1 Bryophyta St, 1 *Larix decidua* N, 2 *Larix decidua* N-P, 4 FL-P, 1 B-P indet., 1 Pinaceae Misp, 1 FL-P indet. (3.5)	−28.4	0.47	3575 ± 26	3732–3972
121856 (g)	1001-1-B-11-2 (17)	25.100	5 *Larix decidua* N-P, 1 *Pinaceae* Misp, 1 Bryophyta St, 4 L-P (2.9)	−28.3	0.63	3905 ± 22	4250–4416
116852 (g)	1001-1-B-11-CC (6)	25.986*	n.d.	−28.6	0.36	4074 ± 25	4442–4796
135232 (g)	1001-1-B-12-1 (41.75)	26.919	1 *Pinus cembra* SS, 1 Bryophyta St, 1 Pinaceae N, 1 FL-P (cf. *Fagus sylvatica*) (2.4)	−27.1	0.40	4469 ± 27	4976–5287
121855 (g)	1001-1-B-12-2 (14.25)	27.64	14 Bryophyta St, 1 L-P, 9 T-P indet. (2.1)	−25.9	0.71	4786 ± 23	5476–5585
121854 (g)	1001-1-A-15-1 (24.5)	28.64	1 *Larix decidua* N-P, 1 *Abies alba* N-P, 1 *Pinus* BS, 4 L-P, 3 Bryophyta St, 16 T-P indet. (1.8)	−26.8	0.17	5128 ± 37	5749–5988
121853 (g)	1001-1-A-15-2 (91)	30.30	1 *Juniperus* N-P, 3 *Abies alba* N-P, 1 B-P (2.2)	−22.9	0.62	5574 ± 23	6303–6399
121863 (g)	1001-1-A-16-1 (73)	32.00	2 *Picea abies* N-P (2.6)	−26.7	0.84	6018 ± 23	6790–6941
121861 (g)	1001-1-A-17-1 (69)	35.05	3 *Abies alba* T-P (4.1)	−27	1.00	6361 ± 24	7171–7414
116853 (g)	1001-1-B-16-CC (5.25)	35.341*	n.d.	−28	0.99	6424 ± 25	7280–7423
121852 (g)	1001-1-A-18-1 (51)	37.55	3 *Abies alba* N-P, 1 Pinaceae BS, 3 Bryophyta St (2.1)	−27.8	0.35	6669 ± 37	7433–7609
121851 (g)	1001-1-B-19-2 (16)	38.88	1 *Picea abies* N-P, 1 Bryophyta St, 3 T-P indet. (2.5)	−24.6	0.54	7624 ± 25	8374–8452
121859 (g)	*1001-1-A-19-1 (40)*	*40.00*	*1 Conifer T* (cf. *Picea abies*) (78.6)	*–27.8*	*1.00*	*8282 ± 25*	*9137–9416*
135234 (g)	1001-1-A-19-1 (51)	40.111	1 Lamiaceae St-P, 1 Pinaceae Pe, 3 B-P (3.7)	−26.5	0.86	7768 ± 25	8454–8598
121850 (g)	1001-1-B-21-2 (34.5)	42.35	9 T-P indet., 2 B-P, 17 Bryophyta St, 31 L-P (53)	−30.9	1.00	8414 ± 25	9321–9526
131460 (GIS)	1001-1-B-22-1 (74)	44.611	1 Pinaceae BS, 1 T indet. (2.2)	n.m.	0.10	8756 ± 89	9545–10 147
121862 (g)	1001-1-B-23-1 (72)	45.78	1 *Salix* T-P (24.1)	−30.4	1.00	9689 ± 26	10 880–11 202
116854 (g)	1001-1-B-23-CC (2)	46.976*	n.d.	−25.3	1.00	9841 ± 29	11 198–11 313
116855 (GIS)	1001-1-B-24-CC (4.25)	48.526*	n.d.	−20.1	n.m.	10 363 ± 86	11 880–12 607
116856 (g)	1001-1-B-25-CC (8.25)	50.551*	n.d.	−29.2	0.24	10 718 ± 36	12 682–12 748

* Core catcher samples were projected to the corresponding depth, if possible; otherwise, they were set at the bottom of the corresponding core section.

with OxCal 4.4.4 (Bronk Ramsey, 2009), and were thereafter transformed into calibrated years BP (before present: before 1950 CE) according to the calibration curve IntCal20 (Reimer et al., 2020). The Bacon v3.0.0 software package for R (Blaauw and Christen, 2011) was used for Bayesian age–depth modeling; however, two radiocarbon dates (ETH-121857 and ETH-121859; see Table 2) were excluded from the age–depth model, as they were sampled within the base of event deposits (see Sect. S6 and respective Fig. S2 for more details). Furthermore, 17 radiocarbon dates from the HAS_2016-1 sediment core (Lauterbach et al., 2023) were included into the total age–depth model by projecting them onto the H^3 composite core profile using tie points (see Table S5) to cover the upper 15 m of the stratigraphy.

4 Results

4.1 Seismic airgun units

The seismic airgun data show a seismic stratigraphy with three distinct seismic units (SUs) characterized by five different seismic facies (F1–F5, Table S4) at the coring site (Fig. 2): SU1 is a ∼ 12 m thick acoustically laminated, high-amplitude reflection package (F1) with limited lateral continuity. On the whole basin scale, SU1 also comprises several zones at different stratigraphic levels with a few meter-thick, semi-transparent, and non-continuous reflections (F2) with variable amplitudes and hummocky to deformed geometries (e.g., shot points (SPs) 1260–1370, 1420–1550, and 1750–1990 in Fig. 2a and b; 3270–3290, 3235–3250, and 3190–3225 in Fig. 2c and d). At the HAS_2016-1 site, the SU1-to-SU2 boundary corresponds to the base of E2 (Fig. 2b). SU2 shows more diffuse low-amplitude reflections (F3) above the 25 ms^{-1} TWT level dominated by a bubble pulse (green arrows in Fig. 2), with higher amplitudes towards the top of the unit. In the south of the N–S seismic profile, SU2 shows northward-dipping reflections with moderate amplitudes (F4) and moderate lateral continuity, occasionally interlayered with chaotic facies. The seismic signal penetration to greater depth is generally limited by seismic attenuation, related to MTD bodies (as described in core HAS_2016-1 (Lauterbach et al., 2023) and the following sections) and free gas in the pore space of the sediment causing acoustic blanking. A ∼ 250 m wide "seismic window" near the Hallstatt fan (SP 1270–1390 in Fig. 2a, b) images the deeper subsurface (SU3, down to ∼ 40 m b.l.f.) with northward-inclined medium-amplitude reflections (F5) with low lateral continuity (Fig. 2a, b).

4.2 Borehole logging units

Nine logging units were defined based on the downhole logging measurements collected in hole H^3 B (Fig. 3). Logging Unit 1 (LU1, 124–131 m b.l.l.) is characterized by intermediate GR values of 55.1 ± 2.9 gAPI and a downhole-decreasing trend in MS (with overall low values of $0.9 \pm 0.1 \times 10^{-4}$ SI – Système International – on average). The turning point with the lowest MS value, after the decreasing trend, defines the boundary to Logging Unit 2 (LU2). LU2 (131–135.6 m b.l.l.) shows on average low MS values of $0.8 \pm 0.1 \times 10^{-4}$ SI and very low GR values of 39.2 ± 5.6 gAPI and consist first of an interval of low MS and GR values until 135.2 m b.l.l. followed by a sharp increase, up to a peak in MS value of 1.52×10^{-4} SI, indicating the transition to Logging Unit 3 (LU3). LU3 (135.6–139.5 m b.l.l.) consists of increased MS values of $1.1 \pm 0.1 \times 10^{-4}$ SI and stable GR values of 60.3 ± 3.7 gAPI encircled by high GR values at the top. The transition to Logging Unit 4 (LU4) is defined as the turning point towards low GR value, with a peak in K and a low in MS values. LU4 (139.5–140.9 m b.l.l.) shows a thin layer with low GR values centered around a minimum value of 37.2 gAPI with intermediate MS values ($1.1 \pm 0.1 \times 10^{-4}$ SI on average). The increase in GR value at the bottom of the thin layer, as well as the low MS value indicate the transition to Logging Unit 5. LU5 (140.9–145 m b.l.l.) comprises high GR values (74 ± 7.9 gAPI on average) with two prominent thin layers with GR values of up to 85.4 gAPI and an MS trough in between. Overall, LU5 includes spikey and high MS values with an average of $1.3 \pm 0.2 \times 10^{-4}$ SI. The transition to Logging Unit 6 is indicated with the transition towards lower GR values and a peak in MS values. LU6 (145–149.9 m b.l.l.) comprises high GR values (64 ± 5.9 gAPI on average) with one prominent thin layer of increased GR values of up to 73.6 gAPI. The MS values show intermediate values of $1.1 \pm 0.1 \times 10^{-4}$ SI on average. The transition to Logging Unit 7 is indicated with the transition towards increased GR values and a low in K and MS values. LU7 (149.9–157.3 m b.l.l.) also indicates enhanced MS values of $1.3 \pm 0.2 \times 10^{-4}$ SI (based on the 149.9–151.6 m b.l.l.) as well as a peak-shaped evolution of high GR values (on average of 68 ± 8.5 gAPI). The transition point to Logging Unit 8 (LU8) is defined after the GR trough of 49.62 gAPI, towards more stable GR values. LU8 (157.3–165.8 m b.l.l.) shows very stable and intermediate GR values of 56.46 ± 1.9 gAPI and lower and spikey MS values of $1 \pm 0.1 \times 10^{-4}$ SI. The transition to Logging Unit 9 (LU9) is the lowest MS value before the onset of an increasing trend of MS and GR values. LU9 (165.8–173.2 m b.l.l.) shows increased GR values of 66.3 ± 3.3 gAPI and increased MS values of $1.2 \pm 0.1 \times 10^{-4}$ SI.

4.3 Lithostratigraphic units

The sedimentary succession comprises two major lithostratigraphic units: Unit 1 (Holocene, with six subunits) and Unit 2 (Late Pleistocene). The sediments are mainly composed of carbonate mud, interbedded with multiple millimeter- to centimeter-thick light-gray clayey-silt graded deposits (further referred to as turbidites as interpreted and used by Lauterbach et al., 2023, and Strasser et al., 2020). Further-

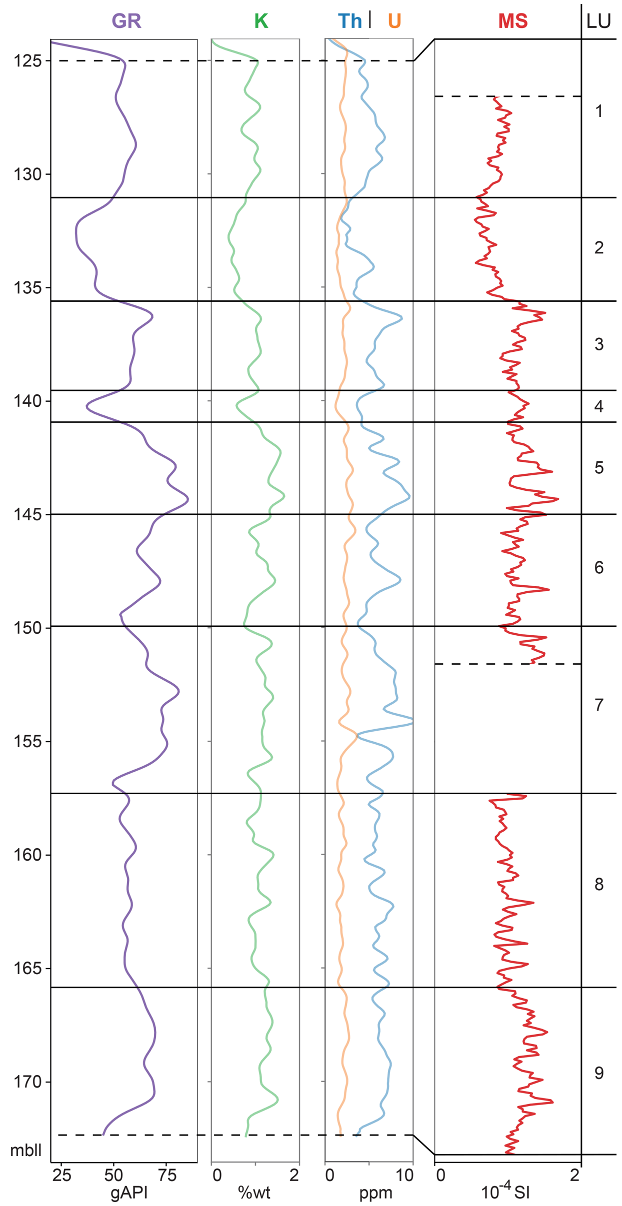


Figure 3. Borehole logging for the sediments of Lake Hallstatt (Salzkammergut, Austria) with natural gamma radiation (GR); magnetic susceptibility (MS); and U, K, and Th concentrations. The numbers 1–9 represent the identified borehole logging units (LUs). The sections with no MS data in interval 1 and interval 7 were discarded (measurement inside metal casing).

more multiple > 0.3 m thick deposits occur with a graded, coarser-base, homogenous body and clay cap overlying cohesive mixed sedimentary layers interpreted as co-genetic turbidites (cf. Lauterbach et al., 2023) and mass-transport deposits (MTDs). The labeled events differentiated by visual changes in color, grain size, lamination thickness, structure, and MSCL data (γ density and magnetic susceptibility; see Figs. 4 and 5, Table S6, and Sect. S3). The presented ages are derived from the age–depth model, using precise radiocarbon dates performed on plant remains (see Sect. 3.7).

Unit 1 – Holocene, 0–47.60 m c.d. (present day to 11 623 ± 150 cal BP)

Subunit A (0–2.36 m composite depth (m c.d.); bottom: 304 ± 28 cal BP) consists of laminated to very thin bedded dark-gray clayey–silty carbonate mud, interbedded with millimeter- to centimeter-thick graded turbidites. It shows very low mean density values of $\sim 1.30\,\mathrm{g\,cm^{-3}}$ and a drastic increase in magnetic susceptibility up to $10.57 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$. The transition phase ($\sim 5$ cm, 2.4–2.45 m c.d.) to subunit B is a striking color change toward yellowish as well as to lower MS values ($\sim 3.95 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$) and higher-density values (Fig. 4). E1, mainly present close to the Hallstatt alluvial fan (Lauterbach et al., 2023), within subunit A is not indicated, as it shows < 0.3 m thickness at the deep basin. A slight nick point within the age–depth model indicates a slight decrease in sedimentation rate for subunit A compared to subunit B.

Subunit B (2.36–6.87 m c.d.; bottom: 711 ± 34 cal BP) is a prominent yellowish-gray clastic carbonate mud interval of ~ 4.5 m (2.4–6.87 m c.d.) with faintly millimeter- to centimeter-scale laminated sediments (Fig. 5). This sequence shows a slightly enhanced mean density value of $1.43\,\mathrm{g\,cm^{-3}}$ compared to the two adjacent subunits A and C and a decreasing trend towards subunit A. The transition phase of subunit B to subunit C (6.76–6.87 m c.d.) is a striking color change from more yellowish to blackish, gray colors, a drop in density values and MS values, and a decrease in sedimentation rate within subunit C. The sedimentation rates of subunits B and A show the highest sedimentation rates.

Subunit C (6.87–18.23 m c.d.; bottom: 2239 ± 82 ka cal BP) consist of laminated to very thin bedded dark-gray clayey–silty carbonate mud (very similar to subunit A), interbedded with millimeter- to centimeter-thick graded turbidites. The background sedimentation shows a mean density of $1.44\,\mathrm{g\,cm^{-3}}$ and mean MS of $4.1 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$ with the highest values below E2 ($10.85 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$). Subunit C comprises two major mass-transport deposits (E2: ~ 5.1 m thick; E3: ~ 2.7 m thick; see Table S6) forming respective MTDs containing pebbles (up to 3 cm in diameter) and related co-genetic turbidites. E2 shows a distinct bipartite structure in both holes (A and B) which is separated by a sandy organic-rich interval (9.12–9.42 m c.d.). The basal part (9.42–12.74 m c.d.) shows a chaotic mixture at the bottom of a mainly sandy matrix with pebbles which transitions to a sandy matrix with pebbles and mud clasts, with partly intact laminations or vertical laminations and soft sediment deformation and sand package. The overlying interval shows amalgamated sandy deposits with macro remains, with decreasing thickness towards the overlying turbidite (7.64–9.12 m c.d.), which has a distinct homogenous structure with a very thin mud cap (< 0.5 cm).

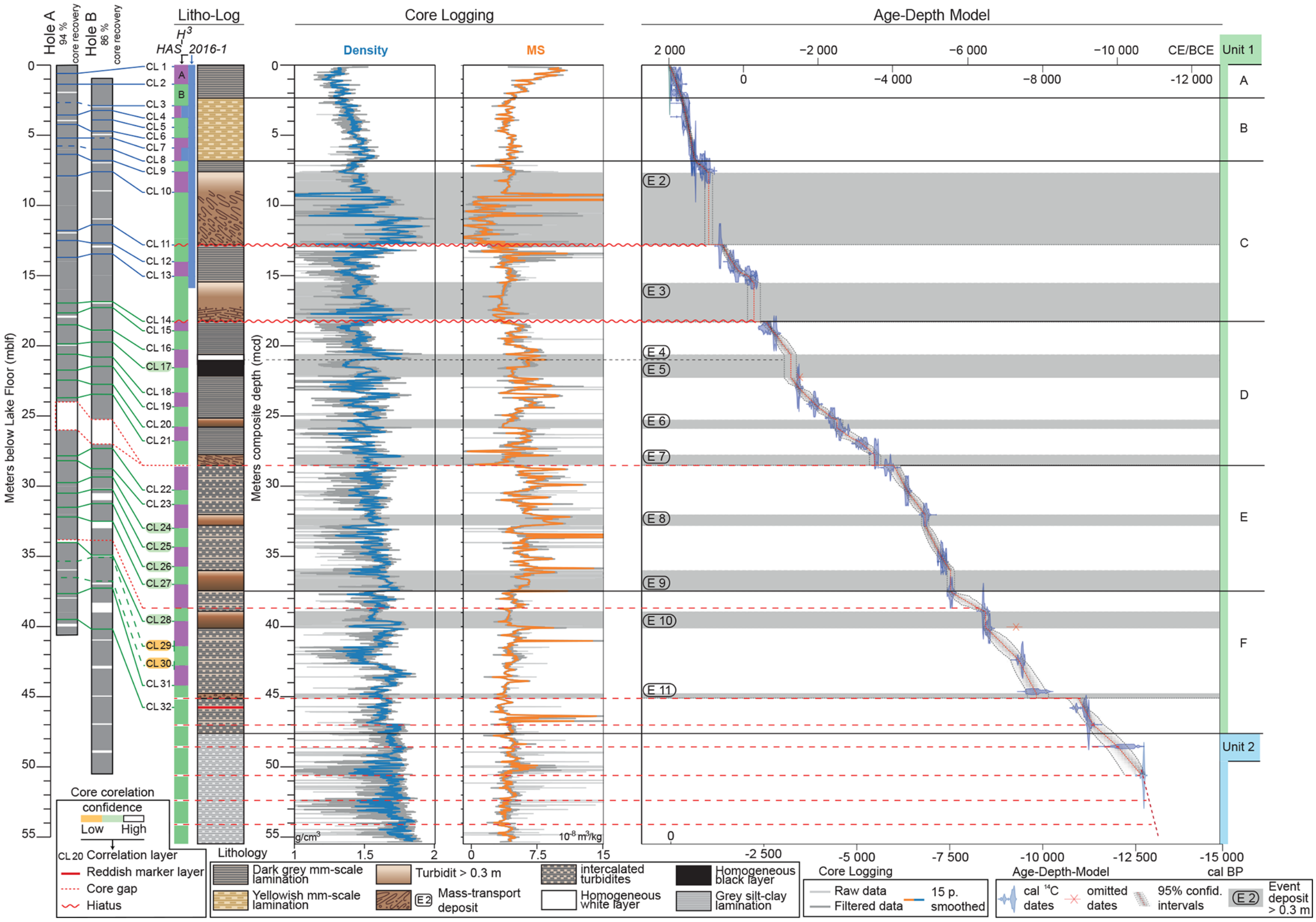


Figure 4. Composite profile overview for the sediments of Lake Hallstatt (Salzkammergut, Austria). From left to right: core recovery of both boreholes and correlation lines (blue: correlation with HAS_2016-1 core possible; green: correlation possible only between the H^3 cores A and B). Composite profile of the borehole used (indicated in green and purple). Simplified lithology log for the composite profile (with eight major lithology types, including event deposits). Whole-round measured density. Magnetic susceptibility. Age–depth model based on 35 radiocarbon (^{14}C) dates, with the two ^{14}C dates shown in red omitted. Identified lithological units for the Late Pleistocene (blue) and Holocene (green).

In comparison to the HAS_2016-1 core (Lauterbach et al., 2023), we observe a much coarser grain size and less deformation structures within the basal part of E2. The base of E2 shows erosional features and missing laminations compared to the HAS_2016-1 core, suggesting a hiatus of ∼ 150–550 years based on the age–depth model (Fig. 4). Event 3 (E3) also shows a bipartite structure with a basal part and an overlying turbidite. The basal part varies strongly between holes A and B within the individual parallel core segments, demonstrating a high spatial heterogeneity of the event deposit. Hole A shows a small (∼ 1 cm) sandy base overlain by subvertical laminations and folded laminas (∼ 80 cm), which is followed by the turbidite (> 1.9 m), a homogenous package. The base of the turbidite was not retrieved in hole A. In hole B, the basal part (∼ 45 cm, 17.76–18.23 m c.d.) consists of a sandy matrix with some pebbles mud clasts, with the very bottom part not being retrieved. The top part of the basal part comprises an amalgamated organic-rich interval (∼ 45 cm, 17.30–17.76 m c.d.) with centimeter-thick sandy intersections towards the turbidite. The turbidite is a ∼ 1.8 m thick homogenous package with a thin (< 0.5 cm) mud cap. The background sedimentation rate between E2 and E3 indicates a slight increase in sedimentation after E3 and an increasing trend towards E2. Also, the transition to subunit D at the base of E3 (18.23 m c.d.) likely shows a hiatus of up to ∼ 600 years based on the age–depth model.

Subunit D (18.23–28.47 m c.d.; bottom: 5544 ± 93 ka cal BP) is similar in appearance to subunit C with increased mean density values of 1.48 $g\,cm^{-3}$ and MS values of $5.50 \times 10^{-8}\,m^3\,kg^{-1}$. It is intercalated with four homogenous packages (E4, E5, E6, and E7; see Table S6 for depth). E4 and E5 appear to be a stacked event sequence, with an interval of ∼ 2.5 cm in between the deposits which need to be further investigated. E4 is a light-gray, homoge-

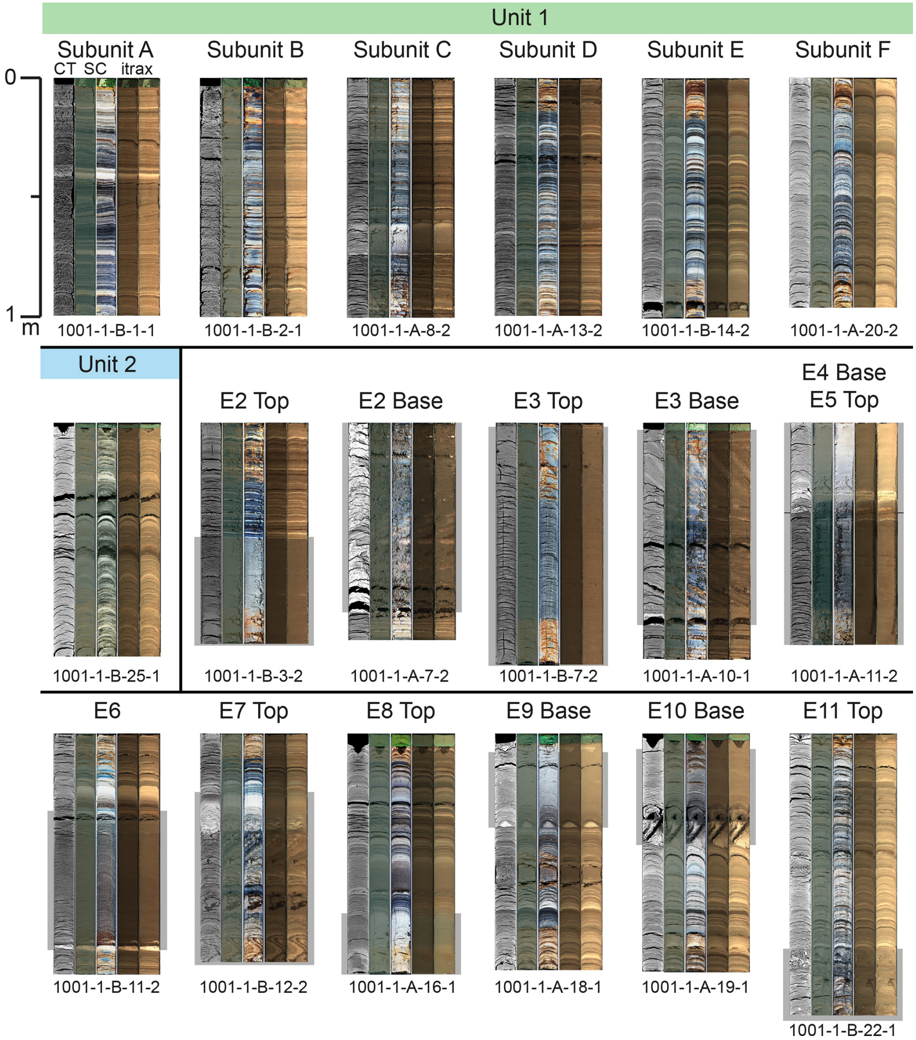


Figure 5. Compilation of drilling core images, for each lithological unit (including subunits) of Lake Hallstatt (Salzkammergut, Austria). Each photographic assemblage shows a computer tomography (CT) image (black less dense, white denser), a smart cube image, a smart cube color-adjusted image, and two ITRAX images (with different light intensities). In addition, a representative core section is shown for each major event deposit (> 0.3 m).

nous package, with a sandy base. E5 is black (directly after core opening) and homogenous with a ∼ 1 cm thick organic-rich layer and a sandy base (< 0.5 cm). E6 is a ∼ 60 cm thick, medium-gray, homogenous package with a ∼ 2 cm thick sandy base and a thin (< 0.5 cm) mud cap. Furthermore, the top part of an MTD (E7: min. 0.7 m thick, base not cored) is present at the bottom of subunit D with a ∼ 14 cm thick light-gray mud sequence and sandy intersections, which are deformed at the lower part of the sequence.

Subunit E (28.47–37.43 m c.d.; bottom: 7525 ± 51 cal BP) indicates an overall change within the Holocene unit to laminated dark-gray clayey–silty carbonate mud interbedded with thicker (millimeter- to centimeter-thick) graded turbidites and two > 0.3 m thick turbidites. The transition occurs likely within the coring gap of ∼ 1 m, and based on the age–depth model ∼ 100–800 years could be missing. The mean density value is 1.55 $g\,cm^{-3}$ and the mean MS value is $6.5 \times 10^{-8}\,m^3\,kg^{-1}$. This shows an increase for both parameters compared to the overlain subunit D. The magnetic susceptibility shows overall the highest values of the composite core and the highest individual MS peaks ($23.59 \times 10^{-8}\,m^3\,kg^{-1}$) of background sedimentation. Additionally, E8 (∼ 74 cm, 32.02–32.76 m c.d.) represents a homogenous, medium-gray to light-gray (∼ 25 cm of the top) mud, with no prominent coarse base. E9 (∼ 1.44 cm, 36–37.44 m c.d.) shows a similar appearance, with a medium-gray, homogenous body and a light-gray upper part (∼ 50 cm) and a 2 cm thick sandy lens as a base.

Subunit F (37.43–47.60 m c.d.; bottom: 11 623 ± 150 cal BP) is a laminated dark-gray clayey–silty carbonate mud interbedded with millimeter- to centimeter-thick graded turbidites similar to subunit E. The mean density value is $1.61\,\mathrm{g\,cm^{-3}}$ and the mean MS value is $4.53 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$. The lowest density values of $\sim 1.3\,\mathrm{g\,cm^{-3}}$ are ~ 43 m c.d. with slightly more blackish sediments compared to the adjacent sediments. E10 (~ 1.14 m, 38.9–40 m c.d.) consist of medium-gray, silty carbonate mud with dark patches and a striking, folded organic-rich, sandy base. At ~ 45 m c.d. E11 occurs (min. 31 cm, 44.76–45.1 m c.d.) and consists of deformed laminations of carbonate mud with chaotically distributed multiple grains (> 0.5 cm) and one layer grains (up to 0.5 cm) in the upper part of E11. In addition, a distinct increase in the density baseline is present at ~ 47 m c.d. to $> 1.69\,\mathrm{g\,cm^{-3}}$.

Unit 2 – Late Pleistocene, ∼ 47.60–55.3 m c.d. (top: 11 623 ± 150 cal BP; bottom: older than 12 682–12 748 cal BP; 50.5 m c.d.)

Unit 2 consists of a Late Pleistocene sedimentary succession comprising laminated very thin bedded (1–3 cm) medium-gray silty–clayey carbonate mud, with several laminated (< 1 cm) intervals and multiple-centimeter-thick light-gray and graded turbidites. Within Unit 2 there are three intervals observable: (i) a mainly finely laminated (< 1 cm) carbonate mud (~ 47.60–~ 50.5 m c.d.) with increased MS values of $\sim 4.63 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$, with the deepest sampled age at the base with 12 682–12 748 cal BP; (ii) a darker colored interval (~ 50–~ 54 m c.d.) with a slightly lower magnetic susceptibility ($\sim 3.94 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$); and (iii) increased density values below ~ 54 m c.d. with $\sim 1.75\,\mathrm{g\,cm^{-3}}$.

5 Discussion

5.1 Core–log (seismic) integration

The integration of seismic airgun, borehole logging, and sediment core data confirms that the boundary between seismic units SU1–SU2 corresponds to the base of the E2 MTD at both the H^3 site and the HAS_2016-1 site (Figs. 2b, d, and 6), across which a downhole increasing MS trend is observed in both the borehole and core logging data (see detailed description of MS-based borehole logging to core logging data correlation in Sect. S7 and Table S7). Hence, the logging unit LU1 corresponds to subunits A and B and to the upper part of SU1. The high-amplitude reflection at ~ 0.197 s TWT depth likely originates from the sharp density contrast at the transition from subunit B to C, which also generally shows increased GR (gamma radiation) values for B and a decrease in GR towards C. The lower part of SU1 at the correlative depth of E2 shows a disrupted-reflection pattern, which can be interpreted as thrusts and ramp features (e.g., Sammartini et al., 2019) within the MTD bodies that thin out towards the deep basin (Fig. 2b). The bipartite nature of E2 (as described in the core data with a turbidite overlying the MTD) is also observed in LU2 with the upper part showing low GR values and transitioning to comparably higher GR values at the base. This is also apparent in the seismic data by a ponding deposit overlying the top of the MTD (thick, solid yellow line in Fig. 2b). The base of E2 at the H^3 site contains rip-up mud clasts and is coarser than at the HAS_2016-1 site. The basal part of E2 at the HAS_2016-1 site shows plastic deformation (Lauterbach et al., 2023), indicative of basin plane deformation (e.g., Sammartini et al., 2019).

SU2 comprises the lower part of subunit C (including E3) and the upper part of subunit D (including E4 and E5; Fig. 6). The C–D subunit boundary correlates very well with the boundary of LU4 to LU5. The thin layer of low GR values at LU4 correlates to the base of E3, representing the MTD of E3. However, neither physical properties nor lithologic characteristics of the subunit boundary and/or the event deposits can be conclusively correlated with the diffuse acoustic facies in the SU2. A positive-amplitude reflection (peak) with reasonable lateral continuity of ~ 1 km occurring at roughly the corresponding depth of E3 at site H^3 is used to tentatively map the top of the MTD E3 through the basin (dashed blue line in Figs. 2b, d and 6). This tentative correlation is supported by the sharp density contrast between the turbidite and the underlying MTD. The turbidite itself, which – in comparison to E2 is thicker (~ 1.8 m) and has higher natural radiation – is not recognizable in the seismic data. Similarly, the base of E3, characterized by lateral heterogeneity of the MTD as observed in holes A and B, cannot be traced (but can tentatively be mapped by the dashed purple line, assuming constant depth of the MTD in Fig. 2b). E4 and E5 are below or near the resolution of the seismic data but observable within LU5 and the upper part of subunit D. E4 shows increased GR, MS, and density values, whereas E5 shows prominent low MS values at the base, which correlates between the borehole logging and core logging dataset (i.e., logging tie points (LTPs) 13–14; Fig. 6; Table S7). The SU2-to-SU3 boundary does not correlate to any specific characteristics of the logged and cored sedimentary succession at site H^3, reflecting the effect of the bubble pulse as an artificial effect, as methodologically described in Sect. 3.1.

Below 25 m b.l.f., the lower part of subunit D correlates very well to LU6 (including E6 and E7; Fig. 6). The MS values of subunit D and LU6 correlate well (see Fig. 6; LTPs 15 to 16) and show overall intermediate MS values, respectively, whereas E6 and E7 show decreased MS values. Also, the MS values in the lower part of LU6 and subunit D show differences which are addressed in Sect. 5.2.

The D–E subunit boundary correlates very well with the LU6–LU7 boundary, with the low MS values at the base of E7. LU7 correlates to subunit E, including E8 (Fig. 6), and is characterized by increased GR and MS values (see LTPs 18 and 19). E8 shows stable GR and density values and a strong peak in MS values. The transition boundary of LU7–LU8 and subunit E–F likely relates to E9, transitioning from increased GR and MS values to intermediate GR and MS values downcore (LTPs 20–27).

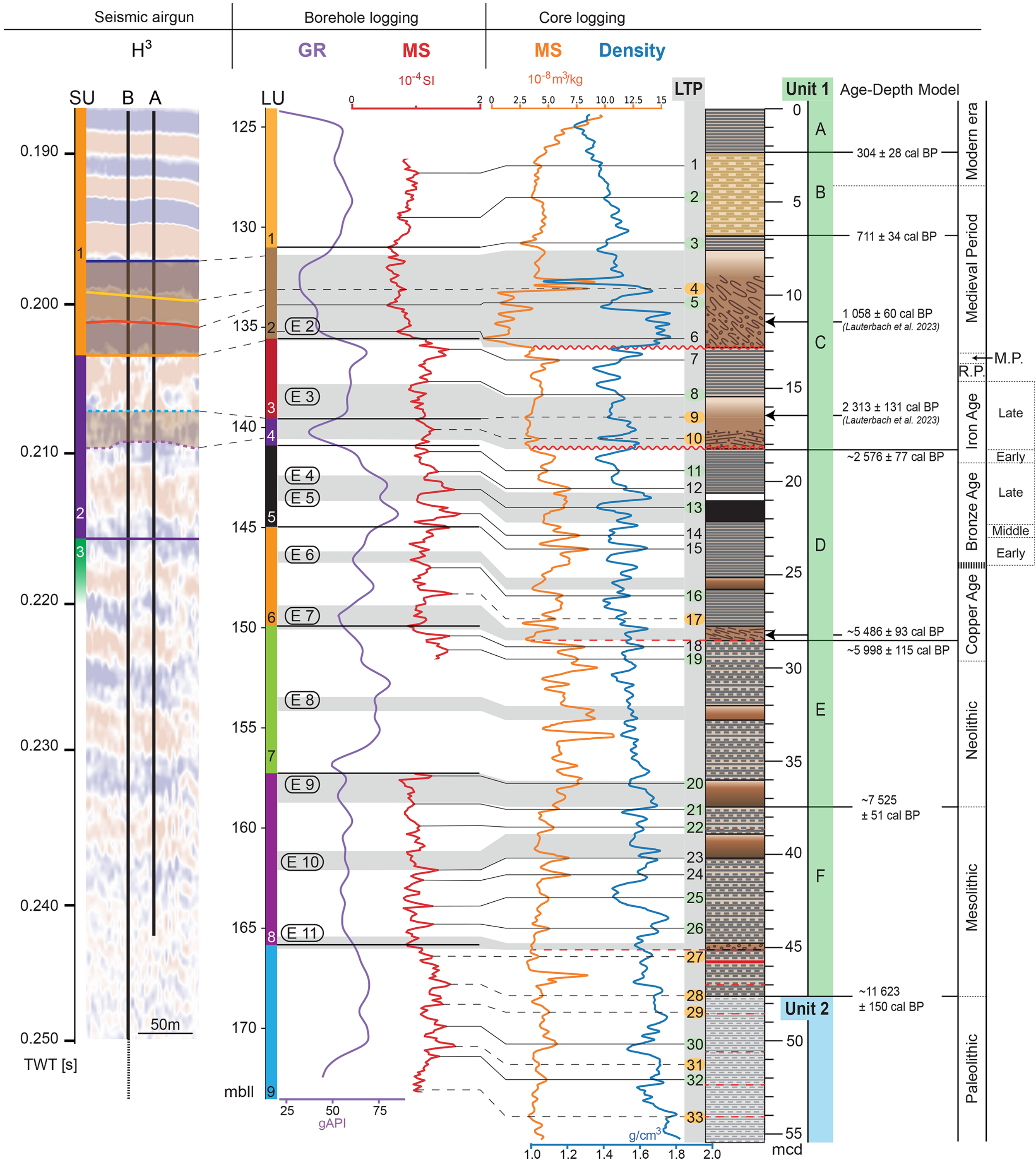


Figure 6. Core–log seismic integration of Lake Hallstatt (Salzkammergut, Austria) with a comparison of seismic airgun and borehole logging units and lithological subunits. Note that the three different datasets are plotted against their respective but different depth scale. The composite core depth scale (m c.d.) is not corrected for extension. Due to this as well as to the appending of core sections, the composite core is ∼ 4 m longer compared to the borehole itself. Dashed and solid lines indicate logging tie points (LTPs) defining the correlation between the logging and core data depending on the confidence level (see detailed description in Sect. S7 and Table S7). The main ages of the lithological boundaries are indicated (based on the Bacon age–depth model), in comparison to archeological periods. See legend in Fig. 4 for lithology. Abbreviations: SU – seismic unit; LU – logging unit; GR – gamma radiation; MS – magnetic susceptibility; TWT – two-way travel time; LTP – logging tie point; M.P. – Migration Period; R.P. – Roman Period.

Below E9, LU8 corresponds to subunit F (including E10 and E11; Fig. 6). The interval between LTPs 22 and 23 will be addressed in the following Sect. 5.2. LU8 and subunit F are characterized by intermediate physical properties values; nevertheless there is a low-density interval ∼ 42 m c.d. and at least one interval prior to E10 with higher MS values.

The transition of LU8–LU9 is based on the transition of intermediate towards increased MS and GR values and likely relates to E11 (Fig. 6; LTPs 27–32). The transition from Unit 1 to Unit 2 (indicating the Pleistocene to Holocene transition; Fig. 4) likely occurs around 47.6 m c.d. based on visual description and after a transition phase of increasing MS and GR values (between E11 and ∼ 47.6 m c.d.) as well as a dominant change in density values. Furthermore, the MS correlation between borehole logging and core logging data between LTPs 27 and 33 is more challenging and will be addressed in the following Sect. 5.2 (also see Sect. S7). LU9 and Unit 2 show increased physical property values until ∼ 52 m c.d., followed by lower physical property values until ∼ 54 m c.d., which are followed by a striking increase in density values.

5.2 Advantages of combining borehole logging and coring in lakes

The borehole logging helped to estimate core extension (Baumgarten et al., 2015) and allows us to constrain the three gaps (Baumgarten et al., 2014), which could not be closed by composing the stratigraphy from boreholes A and B. The correlation of MS peaks between logging and core data across the E7 base (LU6 to LU7; and subunit D–E boundary) reveals that the main coring gap (∼ 25 m b.l.f.) is smaller than 1 m, where challenging drilling conditions occurred in both boreholes A and B – see Sect. S5. The coring gap below E11 (estimated < 1 m during challenging coring operation in borehole B – Sect. S5) is underestimated and could be up to 1 m based on the borehole logging. Also in borehole B, challenging coring operations occurred below E9. The interval between E9 and E10 (LTPs 22–23) suggests that LU8 shows 1 m of more variety, which is not clearly observed within subunit F. This observation strengthens the assumption that no correlation line at the respective depth can be described and that up to 1 m of sediment is missing.

Beside the clear advantages of the borehole logging data there are some key differences compared to the core logging data, such as the evolution of E2 and E3 within the respective datasets. The base of E2 is dominated by a mass-transport deposit (of a carbonate-rich facies) with low-amplitude MS values at the base (Fig. 6). Overlying are higher-amplitude MS values within an organic-rich interval containing sand, observed within the core logging data. In contrast, the borehole logging MS data show a gradual decrease in MS values from the base to the top of the deposit (see more details Sect. S7).

The interval between logging tie points (LTPs) 16 and 18 shows more stable MS values within the borehole logging data compared to more MS fluctuations within the core logging data. These differences might be related to the main coring gap occurring at the base of E7. Furthermore, the interval between LTPs 27 and 28 shows high-amplitude values within the core logging data, which are not observed clearly within the borehole logging data. The lack of high-amplitude values within the borehole logging data could be related to the lower vertical resolution of the borehole logging sensor. Further downcore of LTP 27, mostly only low confidence logging tie points could be identified. This could be related to more appended core segments within the core logging data, using only hole B for the deepest part.

5.3 Lithostratigraphy in chronostratigraphic and prehistoric view

The lithostratigraphic Late Pleistocene–Holocene boundary in Lake Hallstatt occurs at ∼ 47.6 m, with a change from finely laminated (< 1 cm) gray silty–clayey carbonate mud (below) towards laminated dark-gray clayey–silty carbonate mud interbedded with millimeter- to centimeter-thick graded turbidites (above). The Bacon (Blaauw and Christen, 2011) modeled age of 11 623 ± 150 cal BP overlaps the described transition at Mondsee with 11 580–11 540 cal BP (Lauterbach et al., 2011), or the Meerfelder Maar varve chronology (11 590 varve years BP; Brauer et al., 1999). Also, prominent end moraines formed during the Younger Dryas (Egesen Stadial) south of Lake Hallstatt on the Dachstein Massif (locally known as Taubenkar stand; Van Husen, 1977). The bottommost dated sample, with a radiocarbon age range of 12 682–12 748 cal BP at ∼ 50.55 m lies within the Allerød–Younger Dryas boundary which was described at Mondsee with 12 760–12 590 cal BP (Lauterbach et al., 2011). Hence, the Allerød–Younger Dryas transition likely occurs at ∼ 50.55 m c.d., which aligns with a decrease in GR and MS values downcore.

The Late Pleistocene (Unit 2 and LU9) covers the final part of the Upper Paleolithic (until 11 623 cal BP, Fig. 6), followed by six subunits (subunit A–F) and eight logging units (LUs 1–8) formed during the Holocene. The Early Holocene (subunit F, LU8) covers the Mesolithic and shows moderate fluctuations in physical properties (Fig. 6). The subsequent intervals – (i) subunit E/LU7 (onset at ∼ 7525 ± 51 cal BP), (ii) subunit D, lower part/LU6 (onset at 5998 ± 115 cal BP), (iii) subunit D, upper part/LU5 (onset at ∼ 3769 ± 91 cal BP), and (iv) subunit C/LU3 and LU4 (onset at ∼ 2576 ± 77 cal BP) – show four distinct phases of drastic changes in physical properties (Fig. 6). We observe strong variations in the sedimentation rate (indicated by the changing slope angle in the age–depth model) and multiple large-scale mass movements. Chronologically, these four intervals cover the prehistoric and large parts of the historical period (from the Neolithic to Medieval periods, Fig. 6) and thus include the onset and development of human activity in the Hallstatt area. The oldest evidence for human activity in the vicinity of Lake Hallstatt dates to the 7th and 6th millennium BP (Festi et al., 2021). The visually observed sedimentary change (as described in Sect. 4.3), as well as the physical property change at the transition towards the Copper Age (6250–4150 cal BP; subunit E (upper part) and subunit D (lower part)/LU6) will help to better characterize the role of human influence in this early phase. It is important to note that archeological as well as paleoecological data indicated the possibility of salt extraction as early as the 7th/6th millennium BP (Festi et al., 2021). Fully developed large-scale underground salt mining is evidenced from ∼3400 cal BP (Middle/Late Bronze Age) onwards. The Bronze Age and Early Iron Age mining phases were disrupted by large-scale mass movements several times (Festi et al., 2021; Grabner et al., 2021; Knierzinger et al., 2021). The highly resolved sedimentary record presented here will help elucidate the impact of mining as well as societal reaction to geohazards at a high chronological resolution as well as the chronology of the Late Iron Age salt mining in Hallstatt and the question of a continuity into Roman times (cf. Festi et al., 2021).

The Late Holocene consisting of LU1/subunit B and subunit A, covers the High to Late Medieval period and Modern Era, with the onset of subunit B (∼711 ± 34 cal BP) likely being influenced by increased human environmental interaction, such as increased salt mining with related timber exploitation and forest clearance, transport of timber and salt on the lake (Festi et al., 2021; Urstöger, 2000), and potential river diversions further upstream close to Lake Altaussee (Lamer, 1998). The change to subunit A around the mid-17th century CE could be related to systematic forest management (Lauterbach et al., 2023; Urstöger, 2000).

6 Conclusions and outlook

The Hipercorig system successfully drilled a high-resolution Late Pleistocene to Holocene sediment succession of Lake Hallstatt and revealed 10 unique major event deposits, with more than 0.3 m thickness (E2–E11) and performed borehole logging through the Hipercorig system for the first time. The borehole logging and sediment logging reveal several dynamic phases during the Holocene, with changing accumulation rate and physical property fluctuations, and correlate very well with each other. Also, the upper 15 m of the composite profile correlate very well with the HAS_2016-1 core (Lauterbach et al., 2023). However, the E2 and E3 event deposits show high spatial heterogeneity.

The inner Alpine landscape of Lake Hallstatt, within the UNESCO World Heritage region, is described as a fascinating geomorphological laboratory (Weidinger and Götz, 2022). The successful drilling campaign of the Hipercorig platform enables a high-resolution multi-proxy and multi-disciplinary-based analysis of the Late Pleistocene to Holocene sedimentary succession at Lake Hallstatt. The international research team will proceed on several main frontiers: (i) archeology, (ii) paleoclimate, and (iii) paleogeohazards. This should be done in order to link the H^3 sediment sequence to archeological findings and to better understand human–environment interaction as well as to disentangle the probable onset and impact of human activities from climatic and environmental drivers within the surroundings of Lake Hallstatt. In combination with existing neighboring lake research projects (e.g., Mondsee, Lake Altaussee) it will be possible to extract local from regional signals and compare them. Establishing a high-resolution event record for Lake Hallstatt will enable the analysis of the magnitude and frequency of natural hazards and contribute to a regional/-global climatic sediment archive on a Holocene timescale in order to better understand the long-term changes within intermountain lake systems.

Code availability. The code for visualizing the MSCL data is available at https://github.com/Marcel1415/splice (last access: 24 May 2023; DOI: https://doi.org/10.5281/zenodo.7966002, Ortler, 2023).

Data availability. Preliminary data outlined in this report are not publicly available as they are still being evaluated and expanded. Upon completion, all data will be made available when scientific papers and reports are published.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/sd-33-1-2024-supplement.

Author contributions. MS, KK, AB, SCF, and HR designed the research and secured funding. MO, JK, SCF, AB, IH, JNH, and MS analyzed the data. MO and AB conducted the core descriptions, and MO developed the composite stratigraphy. MO wrote the paper and produced the figures with input from all the co-authors.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. This research was supported by the Austrian Academy of Sciences (ÖAW) through (i) the ÖAW-ESS Project FACEALPS: 3500 years of man-environmental interrelation in the UNESCO World heritage region of Hallstatt–Dachstein/Salzkammergut (PI: Kerstin Kowarik; https://facealps.

wordpress.com, last access: 24 May 2023), (ii) the ÖAW-ESS-IGCP Project S^4LIDE – Hallstatt Studying the Significance of Subaqueous Slides in Lake Hallstatt (https://www.uibk.ac.at/en/geologie/research/sediment/research/projects/s4lide-hallstatt/, last access: 24 May 2023), and (iii) the ÖAW Project Hipercorig Hallstatt History (H^3): Accessing a deep time window of Lake Hallstatt's preHistory (PI: Michael Strasser; https://www.uibk.ac.at/en/geologie/research/sediment/research/projects/h3-project/, last access: 24 May 2023). We also want to thank the project supporters: Freunde des Naturhistorischen Museums Wien, Österreichische Bundesforste, Salinen Austria AG, Salzwelten GmbH, Fraunhofer IEG (Volker Wittig, Timo König, Sebastian Krusenbaum), the German Scientific Earth Probing Consortium (GESEP), and the UWITEC GmbH (especially the drilling operators: Richard Niederreiter and Daniel and Martin Niederreiter). We also thank the drilling supervisor Ulli Raschke as well as Markus Erhardt, Gerald Degenhart, and Wolfgang Recheis for the medical CT measurements at the Medical University of Innsbruck; Hannah B. Stanger for the preparation of the ^{14}C samples; Werner H. Schoch for the determination of wood remains; Felix Lang for information on the Roman Period in our research area; and Chiara Ide, Nicholas J. Lewis, Julia Rechenmacher, Johanna G. Pöll, Markus Niederstätter, Anja B. Grießer, and Hannah Braun for assisting during the core opening week. Moreover, we want to thank crucial project members Martin Töpfer, Daniel Brandner, and Flavio S. Anselmetti for their support and discussions. Copernicus Land Monitoring Services and http://data.gv.at (last access: 12 January 2021) are thanked for providing the DEM data. IHS Markit is acknowledged for their educational grant program providing the Kingdom seismic interpretation software.

Financial support. This research was supported by the Austrian Academy of Sciences (ÖAWESS Project FACEALPS, ÖAW-ESS-IGCP Project S^4LIDE and the ÖAW Project Hipercorig Hallstatt History), the Freunde des Naturhistorischen Museums Wien, Österreichische Bundesforste, Salinen Austria AG, Salzwelten GmbH, Frauenhofer IEG, the German Scientific Earth Probing Consortium (GESEP), and UWITEC GmbH.

Review statement. This paper was edited by Nadine Hallmann and reviewed by two anonymous referees.

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V., and Prakash, A.: Cross-Chapter Paper 5: Mountains, edited by: Pörtner, H. O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2273–2318, https://doi.org/10.1017/9781009325844.022, 2022.

Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M. D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R. P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J. G., Cassou, C., Cherchi, A., Collins, W., Collins, W. D., Connors, S. L., Corti, S., Cruz, F., Dentener, F. J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F. J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestvedt, J. S., Fyfe, J. C., Gillett, N. P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J. M., Hamdi, R., Hawkins, E., Hewitt, H. T., Hope, P., Islam, A. S., Jones, C., Kaufman, D. S., Kopp, R. E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T. K., Meinshausen, M., Min, S.-K., Monteiro, P. M. S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A. C., Ruiz, L., Sallée, J.-B., Samset, B. H., Sathyendranath, S., Seneviratne, S. I., Sörensson, A. A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehle, S., Zhang, X., and Zickfeld, K.: Technical Summary, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B.: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 33–144, https://doi.org/10.1017/9781009157896.002, 2021.

Barsch, E., Kowarik, K., Rodler, K., Hörweg, C., Reschreiter, H., Sattmann, H., and Walochnik, J.: First molecular data on the human roundworm Ascaris lumbricoides species complex from the Bronze and Iron Age in Hallstatt, Austria, Sci. Rep., 13, 12055, https://doi.org/10.1038/s41598-023-38989-8, 2023.

Baumgarten, H., Wonik, T., and Kwiecien, O.: Facies characterization based on physical properties from downhole logging for the sediment record of Lake Van, Turkey, Quaternary Sci. Rev., 104, 85–96, https://doi.org/10.1016/j.quascirev.2014.03.016, 2014.

Baumgarten, H., Wonik, T., Tanner, D. C., Francke, A., Wagner, B., Zanchetta, G., Sulpizio, R., Giaccio, B., and Nomade, S.: Age–depth model of the past 630 kyr for Lake Ohrid (FYROM/Albania) based on cyclostratigraphic analysis of downhole gamma ray data, Biogeosciences, 12, 7453–7465, https://doi.org/10.5194/bg-12-7453-2015, 2015.

Behrends, K., Heeschen, K., Kunkel, C., and Conze, R.: The mobile Drilling Information System (mDIS) for core repositories, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-13663, https://doi.org/10.5194/egusphere-egu2020-13663, 2020.

Beiwl, C. and Mühlmann, H.: Atlas der natürlichen Seen Österreichs mit einer Fläche > 50 ha: Morphometrie – Typisierung – Trophie, Stand 2005, Bundesamt für Wasserwirtschaft, Wien, 147 pp., ISBN 3-901605-29-0, 2008.

Blaauw, M. and Christen, J. A.: Flexible paleoclimate age-depth models using an autoregressive gamma process, Bayesian Anal., 6, 457–474, https://doi.org/10.1214/11-BA618, 2011.

Blöschl, G., Kiss, A., Viglione, A., Barriendos, M., Böhm, O., Brázdil, R., Coeur, D., Demarée, G., Llasat, M. C., Macdonald, N., Retsö, D., Roald, L., Schmocker-Fackel, P., Amorim, I., Bělínová, M., Benito, G., Bertolin, C., Camuffo, D., Cornel, D., Doktor, R., Elleder, L., Enzi, S., Garcia, J. C., Glaser, R., Hall, J., Haslinger, K., Hofstätter, M., Komma, J., Limanówka, D., Lun, D., Panin, A., Parajka, J., Petrić, H., Rodrigo, F. S., Rohr, C., Schönbein, J., Schulte, L., Silva, L. P., Toonen, W. H. J., Valent, P., Waser, J., and Wetter, O.: Current European flood-rich period exceptional compared with past 500 years, Nature, 583, 560–566, https://doi.org/10.1038/s41586-020-2478-3, 2020.

Brauer, A., Endres, C., and Negendank, J. F. W.: Lateglacial calendar year chronology based on annually laminated sediments from Lake Meerfelder Maar, Germany, Quatern. Int., 61, 17–25, https://doi.org/10.1016/S1040-6182(99)00014-2, 1999.

Brigham-Grette, J., Melles, M., Minyuk, P., Andreev, A., Tarasov, P., DeConto, R., Koenig, S., Nowaczyk, N., Wennrich, V., Rosén, P., Haltia, E., Cook, T., Gebhardt, C., Meyer-Jacob, C., Snyder, J., and Herzschuh, U.: Pliocene Warmth, Polar Amplification, and Stepped Pleistocene Cooling Recorded in NE Arctic Russia, Science, 340, 1421–1427, https://doi.org/10.1126/science.1233137, 2013.

Bronk Ramsey, C.: Bayesian Analysis of Radiocarbon Dates, Radiocarbon, 51, 337–360, https://doi.org/10.1017/S0033822200033865, 2009.

Costanza, R., Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., Leemans, R., Redman, C., and Schimel, D.: Sustainability or Collapse: What Can We Learn from Integrating the History of Humans and the Rest of Nature?, AMBIO, 36, 522–527, https://doi.org/10.1579/0044-7447(2007)36[522:SOCWCW]2.0.CO;2, 2007.

Croudace, I. W., Rindby, A., and Rothwell, R. G.: ITRAX: description and evaluation of a new multi-function X-ray core scanner, Geol. Soc. Lond. Spec. Publ., 267, 51–63, https://doi.org/10.1144/GSL.SP.2006.267.01.04, 2006.

Fernández, O., Habermüller, M., and Grasemann, B.: Hooked on salt: Rethinking Alpine tectonics in Hallstatt (Eastern Alps, Austria), Geology, 49, 325–329, https://doi.org/10.1130/G47981.1, 2021.

Festi, D., Brandner, D., Grabner, M., Knierzinger, W., Reschreiter, H., and Kowarik, K.: 3500 years of environmental sustainability in the large-scale alpine mining district of Hallstatt, Austria, J. Archaeol. Sci.-Reports, 35, 102670, https://doi.org/10.1016/j.jasrep.2020.102670, 2021.

Ficker, H., Gassner, H., Achleitner, D., and Schabetsberger, R.: Ectogenic Meromixis of Lake Hallstättersee, Austria Induced by Waste Water Intrusions from Salt Mining, Water Air Soil Poll., 218, 109–120, https://doi.org/10.1007/s11270-010-0627-2, 2011.

Grabner, M., Reschreiter, H., Wächter, E., Mayer, K., Winner, G., and Kowarik, K.: Die verwendeten Holzarten im prähistorischen Salzbergbau von Hallstatt, in: Hallstätter Beziehungsgeschichten. Wirtschaftsstrukturen und Umfeldbeziehungen der bronze-und ältereisenzeitlichen Salzbergbaue von Hallstatt/OÖ. Studien zur Kulturgeschichte von Oberösterreich, vol. 50, edited by: Kowarik, K., 83–96, ISBN 978-3-85474-353-8, 2019.

Grabner, M., Wächter, E., Nicolussi, K., Bolka, M., Sormaz, T., Steier, P., Wild, E. M., Barth, F. E., Kern, A., Rudorfer, J., Kowarik, K., Stöllner, T., and Reschreiter, H.: Prehistoric salt mining in Hallstatt, Austria. New chronologies out of small wooden fragments, Dendrochronologia, 66, 125814, https://doi.org/10.1016/j.dendro.2021.125814, 2021.

Hajdas, I.: Radiocarbon dating and its applications in Quaternary studies, E&G Quaternary Sci. J., 57, 2–24, https://doi.org/10.3285/eg.57.1-2.1, 2008.

Harms, U., Raschke, U., Anselmetti, F. S., Strasser, M., Wittig, V., Wessels, M., Schaller, S., Fabbri, S. C., Niederreiter, R., and Schwalb, A.: Hipercorig – an innovative hydraulic coring system recovering over 60 m long sediment cores from deep perialpine lakes, Sci. Dril., 28, 29–41, https://doi.org/10.5194/sd-28-29-2020, 2020.

IODP depth scales terminology: https://www.iodp.org/policies-and-guidelines/142-iodp-depth-scales-terminology-april-2011/file, last access: 6 February 2023.

Jutzeler, M., White, J. D. L., Talling, P. J., McCanta, M., Morgan, S., Le Friant, A., and Ishizuka, O.: Coring disturbances in IODP piston cores with implications for offshore record of volcanic events and the Missoula megafloods, Geochem. Geophy. Geosy., 15, 3572–3590, https://doi.org/10.1002/2014GC005447, 2014.

Kiefer, C., Oswald, P., Moernaut, J., Fabbri, S. C., Mayr, C., Strasser, M., and Krautblatter, M.: A 4000-year debris flow record based on amphibious investigations of fan delta activity in Plansee (Austria, Eastern Alps), Earth Surf. Dynam., 9, 1481–1503, https://doi.org/10.5194/esurf-9-1481-2021, 2021.

Kiss, A.: Floods and Long-Term Water-Level Changes in Medieval Hungary, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-38864-9, 2019.

Knapp, S., Gilli, A., Anselmetti, F. S., Krautblatter, M., and Hajdas, I.: Multistage Rock-Slope Failures Revealed in Lake Sediments in a Seismically Active Alpine Region (Lake Oeschinen, Switzerland), J. Geophys. Res.-Earth Surf., 123, 658–677, https://doi.org/10.1029/2017JF004455, 2018.

Knierzinger, W., Festi, D., Limbeck, A., Horak, F., Brunnbauer, L., Drollinger, S., Wagreich, M., Huang, J.-J. S., Strasser, M., Knorr, K.-H., Reschreiter, H., Gier, S., Kofler, W., Herzig, C., and Kowarik, K.: Multi-proxy analyses of a minerotrophic fen to reconstruct prehistoric periods of human activity associated with salt mining in the Hallstatt region (Austria), J. Archaeol. Sci.-Reports, 36, 102813, https://doi.org/10.1016/j.jasrep.2021.102813, 2021.

Kück, J., Groh, M., Töpfer, M., Jurczyk, A., and Harms, U.: New geophysical memory-logging system for highly unstable and inclined scientific exploration drilling, Sci. Dril., 29, 39–48, https://doi.org/10.5194/sd-29-39-2021, 2021.

Lamer, R.: Das Ausseer Land: Geschichte und Kultur einer Landschaft, Styria, ISBN 978-3222126130, 1998.

Lankston, R. W.: J. New Display of the 1970 Flathead Lake Seismic Data, 1970 Flathead Lake Seismic Survey, Edited version of the Lankston 2011 Northwest Geology paper, Montana's ScholarWorks, https://scholarworks.umt.edu/flathead/13 (last access: 13 May 2023), 2017.

Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D. L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., Von Grafenstein, U., and Declakes Participants: Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps), J. Quaternary Sci., 26, 253–267, https://doi.org/10.1002/jqs.1448, 2011.

Lauterbach, S., Strasser, M., Kowarik, K., Reschreiter, H., Mandl, G. W., Spötl, C., Plessen, B., and Brauer, A.: Large-scale mass movements recorded in the sediments of Lake Hallstatt (Austria)–evidence for recurrent natural hazards at a UNESCO World Heritage site, J. Quaternary Sci., 38, 258–275, https://doi.org/10.1002/jqs.3472, 2023.

Litt, T., Anselmetti, F. S., Baumgarten, H., Beer, J., Cagatay, N., Cukur, D., Damci, E., Glombitza, C., Haug, G., Heumann, G., Kallmeyer, H., Kipfer, R., Krastel, S., Kwiecien, O., Meydan, A. F., Orcen, S., Pickarski, N., Randlett, M.-E., Schmincke, H.-U., Schubert, C. J., Sturm, M., Sumita, M., Stockhecke, M., Tomonaga, Y., Vigliotti, L., Wonik, T., and the PALEOVAN Scientific Team: 500,000 Years of Environmental History in Eastern Anatolia: The PALEOVAN Drilling Project, Sci. Dril., 14, 18–29, https://doi.org/10.2204/iodp.sd.14.02.2012, 2012.

Mandl, G. W., Van Husen, D., and Lobitzer, H.: Geologische Karte der Republik Österreich 1 : 50 000, Erläuterungen zu Blatt 96 Bad Ischl, Geologische Bundesanst, Wien, ISBN 978-3-85316-061-9, 2012.

Melzner, S.: Ereignis- und Schadenskataster von Sturzprozessen (Steinschlag/Felssturz) in der Gemeinde Hallstatt, in: Arbeitstagung "Angewandte Geowissenschaften an der GBA", edited by: Wimmer-Frey, I., Römer, A., and Janda, C., Bad Ischl, Hallstatt, Gmunden, 19–22 June 2017, Geologische Bundesanstalt, 289–290, ISBN-978-3-85316-092-3, 2017.

Moernaut, J.: Time-dependent recurrence of strong earthquake shaking near plate boundaries: A lake sediment perspective, Earth-Sci. Rev., 210, 103344, https://doi.org/10.1016/j.earscirev.2020.103344, 2020.

Ortler, M.: Marcel1415/splice: v0.2-alpha, Zenodo [code], https://doi.org/10.5281/zenodo.7966002, 2023.

Oswald, P., Strasser, M., Hammerl, C., and Moernaut, J.: Seismic control of large prehistoric rockslides in the Eastern Alps, Nat. Commun., 12, 1059, https://doi.org/10.1038/s41467-021-21327-9, 2021.

Pürstinger, C.: Verbauungsgeschichte Hallstätter Mühlbach und Revision des Gefahrenzonenplans der Marktgemeinde Hallstatt, in: Arbeitstagung "Angewandte Geowissenschaften an der GBA", edited by: Wimmer-Frey, I., Römer, A., and Janda, C., Bad Ischl, Hallstatt, Gmunden, 19–22 June 2017, Geologische Bundesanstalt, 132–139, ISBN-978-3-85316-092-3, 2017.

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer, J. G., Pearson, C., van der Plicht, J., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Turney, C. S. M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S. M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., and Talamo, S.: The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP), Radiocarbon, 62, 725–757, https://doi.org/10.1017/RDC.2020.41, 2020.

Reschreiter, H. and Kowarik, K.: Bronze Age Mining in Hallstatt. A New Picture of Everyday Life in the Salt Mines and Beyond, Archaeologia Austriaca, 103, 99–136, https://doi.org/10.1553/archaeologia103s99, 2019.

Rohn, J., Ehret, D., Moser, M., and Czurda, K.: Prehistoric and recent mass movements of the World Cultural Heritage Site Hallstatt, Austria, Environ. Geol., 47, 702–714, https://doi.org/10.1007/s00254-004-1201-2, 2005.

Rohr, C.: Measuring the frequency and intensity of floods of the Traun River (Upper Austria), 1441–1574, Hydrolog. Sci. J., 51, 834–847, https://doi.org/10.1623/hysj.51.5.834, 2006.

Rohr, C.: Extreme Naturereignisse im Ostalpenraum, Naturerfahrung im Spätmittelalter und am Beginn der Neuzeit, Umwelthistorische Forschungen, vol. 4, ISBN 9783412200428, 2007.

Sabatier, P., Moernaut, J., Bertrand, S., Van Daele, M., Kremer, K., Chaumillon, E., and Arnaud, F.: A Review of Event Deposits in Lake Sediments, Quaternary, 5, 34, https://doi.org/10.3390/quat5030034, 2022.

Sammartini, M., Moernaut, J., Anselmetti, F. S., Hilbe, M., Lindhorst, K., Praet, N., and Strasser, M.: An Atlas of Mass-Transport Deposits in Lakes, in: Submarine Landslides, Geophysical Monograph Series, edited by: Ogata, K., Festa, A., and Pini, G. A., Wiley, 201–226, https://doi.org/10.1002/9781119500513.ch13, 2019.

Schaller, S., Böttcher, M. E., Buechi, M. W., Epp, L. S., Fabbri, S. C., Gribenski, N., Harms, U., Krastel, S., Liebezeit, A., Lindhorst, K., Marxen, H., Raschke, U., Schleheck, D., Schmiedinger, I., Schwalb, A., Vogel, H., Wessels, M., and Anselmetti, F. S.: Postglacial evolution of Lake Constance: sedimentological and geochemical evidence from a deep-basin sediment core, Swiss J. Geosci., 115, 7, https://doi.org/10.1186/s00015-022-00412-1, 2022.

Schnurrenberger, D., Russell, J., and Kelts, K.: Classification of lacustrine sediments based on sedimentary components, J. Paleolimnol., 29, 141–154, https://doi.org/10.1023/A:1023270324800, 2003.

Schorn, A. and Neubauer, F.: The structure of the Hallstatt evaporite body (Northern Calcareous Alps, Austria): A compressive diapir superposed by strike-slip shear?, J. Struct. Geol., 60, 70–84, https://doi.org/10.1016/j.jsg.2013.12.008, 2014.

Stein, S., Geller, R. J., and Liu, M.: Why earthquake hazard maps often fail and what to do about it, Tectonophysics, 562–563, 1–25, https://doi.org/10.1016/j.tecto.2012.06.047, 2012.

Strasser, M., Berberich, T., Fabbri, S., Hilbe, M., Huang, J.-J. S., Lauterbach, S., Ortler, M., Rechschreiter, H., Brauer, A., Anselmetti, F., and Kowarik, K.: Geomorphology and event-stratigraphy of recent mass-movement processes in Lake Hallstatt (UNESCO World Heritage Cultural Landscape, Austria), Geol. Soc. Lond. Spec. Publ., 500, 405–426, https://doi.org/10.1144/SP500-2019-178, 2020.

Stuiver, M. and Polach, H. A.: Discussion Reporting of ^{14}C Data, Radiocarbon, 19, 355–363, https://doi.org/10.1017/S0033822200003672, 1977.

Swierczynski, T., Lauterbach, S., Dulski, P., Delgado, J., Merz, B., and Brauer, A.: Mid- to late Holocene flood frequency changes in the northeastern Alps as recorded in varved sediments of Lake Mondsee (Upper Austria), Quaternary Sci. Rev., 80, 78–90, https://doi.org/10.1016/j.quascirev.2013.08.018, 2013.

Synal, H.-A., Stocker, M., and Suter, M.: MICADAS: A new compact radiocarbon AMS system, Nucl. Instrum. Meth. B, 259, 7–13, https://doi.org/10.1016/j.nimb.2007.01.138, 2007.

Urstöger, H. J.: Hallstatt-Chronik: von den Anfängen bis zum Jahr 2000. Nach Originalchroniken, Veröffentlichungen über Hallstatt, Unterlagen aus dem Museumsarchiv und Berichten von Zeitzeugen, Verlag d. Musealvereins Hallstatt, ISBN 3900998507, 2000.

Van Husen, D.: Zur Fazies und Stratigraphie der jungpleistozänen Ablagerungen im Trauntal, Geolog. Bundesanstalt, 1–130 pp., ISSN 0016-7800, 1977.

Van Husen, D.: LGM and late-glacial fluctuations in the Eastern Alps, Quatern. Int., 38–39, 109–118, https://doi.org/10.1016/S1040-6182(96)00017-1, 1997.

Van Husen, D.: Chapter 2 – Quaternary Glaciations in Austria, in: Quaternary Glaciations – Extent and Chronology, edited by: Ehlers, J., Gibbard, P. L., and Hughes, P. D., Elsevier, vol. 15, 15–28, https://doi.org/10.1016/B978-0-444-53447-7.00002-7, 2011.

Wagner, B., Vogel, H., Francke, A., Friedrich, T., Donders, T., Lacey, J. H., Leng, M. J., Regattieri, E., Sadori, L., Wilke, T., Zanchetta, G., Albrecht, C., Bertini, A., Combourieu-Nebout, N., Cvetkoska, A., Giaccio, B., Grazhdani, A., Hauffe, T., Holtvoeth, J., Joannin, S., Jovanovska, E., Just, J., Kouli, K., Kousis, I., Koutsodendris, A., Krastel, S., Lagos, M., Leicher, N., Levkov, Z., Lindhorst, K., Masi, A., Melles, M., Mercuri, A. M., Nomade, S., Nowaczyk, N., Panagiotopoulos, K., Peyron, O., Reed, J. M., Sagnotti, L., Sinopoli, G., Stelbrink, B., Sulpizio, R., Timmermann, A., Tofilovska, S., Torri, P., Wagner-Cremer, F., Wonik, T., and Zhang, X.: Mediterranean winter rainfall in phase with African monsoons during the past 1.36 million years, Nature, 573, 256–260, https://doi.org/10.1038/s41586-019-1529-0, 2019.

Weidinger, J. T. and Götz, J.: The World Heritage Site Hallstatt-Dachstein/Salzkammergut: A Fascinating Geomorphological Field Laboratory, in: Landscapes and Landforms of Austria, edited by: Embleton-Hamann, C., Springer International Publishing, Cham, 265–276, https://doi.org/10.1007/978-3-030-92815-5_17, 2022.

Wilhelm, B., Rapuc, W., Amann, B., Anselmetti, F. S., Arnaud, F., Blanchet, J., Brauer, A., Czymzik, M., Giguet-Covex, C., Gilli, A., Glur, L., Grosjean, M., Irmler, R., Nicolle, M., Sabatier, P., Swierczynski, T., and Wirth, S. B.: Impact of warmer climate periods on flood hazard in the European Alps, Nat. Geosci., 15, 118–123, https://doi.org/10.1038/s41561-021-00878-y, 2022.

Sci. Dril., 33, 21–31, 2024
https://doi.org/10.5194/sd-33-21-2024
© Author(s) 2023. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

ICDP workshop on the Lake Victoria Drilling Project (LVDP): scientific drilling of the world's largest tropical lake

Melissa A. Berke[1], **Daniel J. Peppe**[2], **and the LVDP team**[+]

[1]Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA
[2]Department of Geosciences, Baylor University, Waco, TX 76706, USA
[+]A full list of authors appears at the end of the paper.

Correspondence: Melissa A. Berke (mberke@nd.edu)

Received: 6 August 2023 – Revised: 29 October 2023 – Accepted: 8 November 2023 – Published: 2 April 2024

Abstract. Lake Victoria, which is bordered by Uganda, Tanzania, Kenya, and has a catchment that extends to Rwanda and Burundi, is home to the largest human population surrounding any lake in the world and provides critical resources across eastern Africa. Lake Victoria is also the world's largest tropical lake by surface area, but it is relatively shallow and without a major inlet, making it very sensitive to changes in climate, and especially hydroclimate. Furthermore, its size creates abundant habitats for aquatic fauna, including the iconic hyper-diverse cichlids, and serves as a major geographic barrier to terrestrial fauna across equatorial Africa. Given Lake Victoria's importance to the eastern African region, its sensitivity to climate, and its influences on terrestrial and aquatic faunal evolution and dispersal, it is vital to understand the connection between the lake and regional climate and how the lake size, shape, and depth have changed through its depositional history. This information can only be ascertained by collecting a complete archive of Lake Victoria's sedimentary record. To evaluate the Lake Victoria basin as a potential drilling target, ~ 50 scientists from 10 countries met in Dar es Salaam, Tanzania, in July 2022 for the International Continental Scientific Drilling Program (ICDP)-sponsored Lake Victoria Drilling Project (LVDP) workshop. Discussions of the main scientific objectives for a future drilling project included (1) recovering the Pleistocene and Holocene sedimentary records of Lake Victoria that document the dynamic nature of the lake, including multiple lacustrine and paleosol sequences; (2) establishing the chronology of recovered sediments, including using extensive tephra fingerprinting and other techniques from deposits in the region; (3) reconstructing past climate, environment, lacustrine conditions, and aquatic fauna, using an integrated multiproxy approach, combined with climate and hydrologic modeling; and (4) connecting new records with existing sedimentary snapshots and fossils exposed in deposits around the lake, tying archaeological, paleontological, sedimentological, tectonic, and volcanic findings to new drilling results. The LVDP provides an innovative way to address critical geological, paleontological, climatological, and evolutionary biological questions about Quaternary to modern landscapes and ecosystems in eastern Africa. Importantly, this project affords an excellent opportunity to help develop conservation and management strategies for regional responses to current and future changes in climate, land use, fisheries, and resiliency of at-risk communities in equatorial Africa.

1 Introduction

Lake Victoria (Uganda, Tanzania, Kenya, Rwanda, and Burundi) is the world's largest tropical lake by surface area ($\sim 68\,000\,\mathrm{km}^2$; Awange et al., 2019) and home to the largest human population around any lake in the world (Fig. 1). In addition to its critical importance for human life and livelihood, the lake's size also acts as a significant barrier to the dispersal of terrestrial fauna across the landscape, and it represents the boundary of several biogeographic zones (e.g., Kingdon et al., 2013). Lake Victoria is also home to a large array of haplochromine cichlid fish, whose diversity, origins, and endemism are the focus of continued significant research (e.g., Seehausen, 1996; Meier et al., 2017; Muschick et al., 2018; Verheyen et al., 2003). Lake Victoria is an extremely sensitive archive of past hydroclimate variability (e.g., Vanderkelen et al., 2018; Beverly et al., 2020; Ogondo et al., 2022). It completely desiccated at least once in the Late Pleistocene (e.g., Johnson et al., 1996) and has likely desiccated and refilled multiple times since it formed (e.g., Scholz et al., 1998). These fluctuations in lake size provided a powerful, dynamic mechanism that forced major changes in human populations and ecosystems around the lake, including range expansion, contraction, and fragmentation of the region's biota, all key drivers of macroevolutionary change (e.g., Tryon and Faith, 2013; Tryon et al., 2015; Faith et al., 2013, 2014, 2016). These processes contributed to the dispersal of early populations of *Homo sapiens* across Africa and the formation and subsequent extinction of diverse large herbivore communities that once roamed an extended Serengeti-like ecosystem. Despite transformative work based on piston cores of the past $< 15\,000$ years (e.g., Johnson et al., 1996; Stager et al., 2002), the complete Quaternary sequence has yet to be collected.

Initial conversations about integrating the rich lacustrine record within the lake with the geological, archaeological, paleontological, and paleoecological data from adjacent terrestrial deposits that formed under conditions substantially more arid than present began in 2015 at a meeting sponsored by Harvard University and organized by Christian Tryon. These initial conversations discussed the possibility of collecting new cores from Lake Victoria that spanned the entire sedimentary history of the lake to bridge the terrestrial and lacustrine records. The Lake Victoria Drilling Project (LVDP) began to take shape as discussions continued amongst the group and with project partner Tanzania Fisheries Research Institute (TAFIRI) and their Director General Ismael Kimirei. Prior to the LVDP workshop in 2022, meetings were also held with members of the LVDP team and faculty at the University of Dar es Salaam (UDSM), including Emmanual Kazimoto, Charles Kasanzu, and Fred Mkuyi, specifically to discuss potential areas of collaboration and needs of both the LVDP and UDSM.

These conversations, early small workshops, and conference presentations culminated in an integrated, multidisciplinary ICDP-supported LVDP workshop in Dar es Salaam, Tanzania, from 25–27 July 2022. The LVDP workshop was attended by ~ 50 scientists from 10 countries (Fig. 2). African interest in the project was high, with $\sim 60\,\%$ of the attendance by African scientists and students from countries including Tanzania, Kenya, South Africa, and Burundi. The workshop focused on the current state of knowledge of the region and future opportunities that would be driven by deep scientific drilling. Workshop participants defined the key scientific questions to be answered by scientific drilling in Lake Victoria and outlined the necessary methodologies for success in those scientific goals; identified education, outreach, community engagement, and partnership-building goals for the project; and discussed logistical considerations, including site selection targets and permitting.

2 Current knowledge and drilling rationale

Lake Victoria straddles the Equator and occupies a broad topographic depression near the center of the eastern African plateau between the eastern and western branches of the East African Rift System (EARS) (Fig. 1). Most of the lake is surrounded by Archaean crust, except for the Winam Gulf in the northeastern corner where faulted Neogene and Quaternary alkali volcanic and sedimentary units dominate the terrain. During the Middle Pleistocene, continued uplift of the western branch of the EARS caused west-flowing regional drainage across the pre-rifted landscape to reverse, resulting in back-ponding and the formation of the precursor to Lake Victoria (Bishop and Trendall, 1966). Continued uplift of the western branch of the EARS has caused the center of the Lake Victoria basin to continually shift eastward since its formation. As a result of this uplift and tilting, the lake's early depositional history is exposed along its modern western margin. Lake Victoria has been interpreted to have formed $\sim 400\,000$ years ago. The current age estimates for the onset of Lake Victoria deposition are based on archaeological sites found within interstratified volcanic, fluvial, and lacustrine deposits in the Kagera River valley west of the lake (Bishop and Posnansky, 1960; Bishop, 1969; Temple and Doornkamp, 1970); Middle Pleistocene-aged lacustrine strata preserved above the eastern side of the modern lake near the Kavirondo Gulf (Kent, 1942); and extrapolations of sedimentation rates from the latest Pleistocene and Holocene portion of the lacustrine record to the entire lake sequence (Johnson et al., 1996).

Due to the nature of its formation and subsequent lake basin evolution, Lake Victoria is quite shallow, with a mean depth of $\sim 40\,\mathrm{m}$ and a maximum depth of $\leq 70\,\mathrm{m}$ (Johnson et al., 1996) (Fig. 3). The combination of an extremely large surface area relative to depth, and the connection between the lake, evaporation, and rainfall, makes the lake highly sensitive to hydroclimate variability. Today, rainfall in the Lake Victoria basin is distributed bimodally, with boreal spring

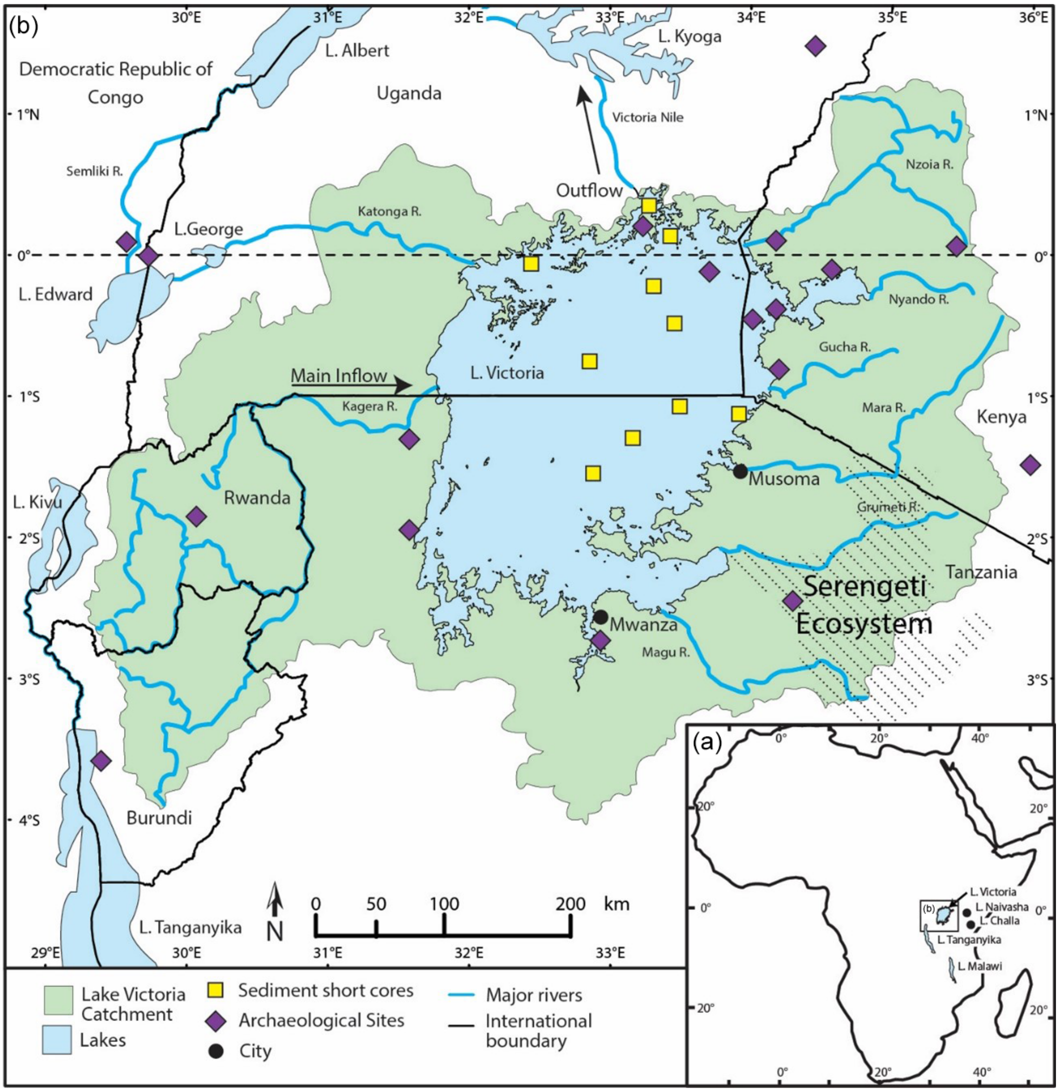


Figure 1. Map of equatorial eastern Africa with the modern extent of Lake Victoria (modified after Beverly et al., 2020, and Tryon et al., 2015). Yellow squares denote previously collected short lake sediment core locations, and purple diamonds mark archaeological sites. See Tryon et al. (2015) for additional site details.

"long rains" and boreal fall "short rains" (Herrmann and Mohr, 2011; Yang et al., 2015). Although the bimodal patterns of rainfall across eastern Africa are commonly linked to seasonal shifts of the Intertropical Convergence Zone (ITCZ), a recognizable ITCZ does not extend across eastern Africa (Nicholson, 2016; Vizy and Cook, 2020). Instead, precipitation in the Lake Victoria basin is created by complex interactions that include sea surface temperatures (SSTs), large-scale circulation, orographic effects, and regional-scale land–lake circulation (e.g., Ogallo and Janowiak, 1988; Mutai and Ward, 2000; Thiery et al., 2014). A significant portion of the water input into Lake Victoria (50 %–80 % of total input) comes from precipitation falling directly over the lake rather than from drainage running into the lake from the catchment area (Flohn and Burkhardt, 1985; Yin and Nicholson, 2002; Tate et al., 2004). Evaporation, while important for the lake's water balance, has low variability in modern Lake Victoria, and hence variations in lake levels are primarily controlled by changes in rainfall (Yin and Nicholson, 2002; Smith and Semazzi, 2014; Beverly et al., 2020).

However, in the past, changes in solar forcing and temperature in the Lake Victoria basin likely considerably effected evaporation, which could have caused changes in lake level (Beverly et al., 2020). Further, studies have linked climate conditions in the Lake Victoria region during parts of the Holocene and latest Pleistocene to teleconnections with the Pacific and Atlantic oceans (e.g., Atlantic Meridional Overturning Circulation (AMOC) and El Niño–Southern Oscillation (ENSO)) and high-latitude processes (e.g., Berke et al., 2012; Stager et al., 2011). The connection between re-

Figure 2. Group photo of LVDP workshop participants at the Julius Nyerere International Convention Centre in Dar es Salaam, Tanzania.

gional climate and evaporation and rainfall on Lake Victoria makes the lake highly sensitive to climate forcing factors such as insolation, SSTs, and atmospheric greenhouse gas levels. This in turn means that intervals when the lake is significantly different in size have profound effects on regional climate, which causes major, nonlinear, and abrupt increases and reductions in lake size (e.g., Beverly et al., 2020). Further, in contrast to the long, narrow, and deep rift lakes with large border faults forming half-grabens (Malawi (750 m), Tanganyika (1500 m), and Turkana (110 m)), Lake Victoria's shallow depth ($\sim$70 m) and large surface area likely result in very different catchment processes (e.g., Beverly et al., 2020) and responses to climate change than the large and deep rift lakes.

The long-core recovery proposed by the LVDP builds upon that of the International Decade of East African Lakes (IDEAL) that began in the 1990s (Johnson, 1991; Cohen et al., 2000). Several piston and gravity cores were recovered in 1995–1996 as part of the IDEAL program (Fig. 1). These cores penetrated 9 m of lacustrine sediment and were stopped by a paleosol dated at $\sim$15 ka (Johnson et al., 1996), due to limitations of the coring techniques at the time. Seismic reflection profiles obtained during the same expeditions revealed that the paleosol extends across the entire lake basin (Fig. 3b), indicating complete desiccation of the lake prior to 15 ka, perhaps during the Last Glacial Maximum (LGM) and extending through Heinrich event 1 (Johnson et al., 1996; Scholz et al., 1998; Talbot and Laerdal, 2000; Stager et al., 2002), when much of Africa experienced relatively cool, arid conditions (e.g., Otto-Bliesner et al., 2014). Existing seismic data reveal at least three more basin-wide paleosols (Fig. 3b). Although paleosols represent unconformities in the lacustrine deposits, which result in gaps in the lake record, they can be correlated and extended to terrestrial outcrops to provide a basin-wide reconstruction of past climates and environments during intervals when the lake was desiccated or considerably smaller than today and lacustrine sedimentation rates were low or erosion occurred (Fig. 3c). Unlike work conducted by the IDEAL project, drilling techniques that are now available to the LVDP are able to penetrate paleosol surfaces and thus not limited by the known lithology, which will help enable the recovery of Lake Victoria's entire sedimentary sequence. Utilizing the paleosols within the lacustrine sequence and correlating them to terrestrial deposits will make it possible to understand the powerful role of periodic desiccation and allow us to fully reconstruct the depositional and climate history of the lake and surrounding region and the impacts on faunal, including human, dispersal and evolution.

Application of drilling methods to recover sediments below the uppermost paleosol will provide the long-term record needed to uncover patterns key to understanding the timing, tempo, and causes of major fluctuations in Lake Victoria's extent throughout the Pleistocene; will clarify its relationship to the evolution of the region's flora and fauna; and will provide a key equatorial record of late Quaternary cli-

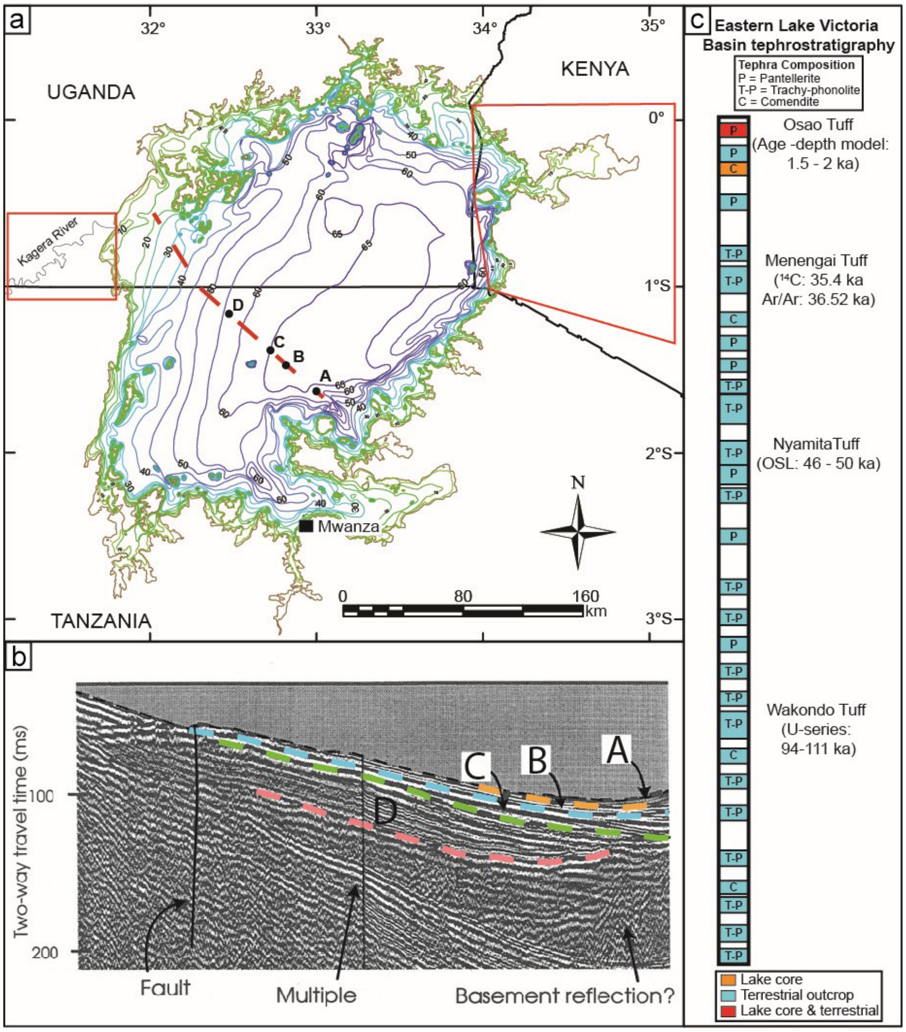


Figure 3. **(a)** Bathymetric map of Lake Victoria with four lacustrine units, labeled A–D, that overlie the Miocene or older basement unit shown in panel **(b)**. Red squares in Uganda and Kenya indicate location of prior terrestrial outcrop research. Dashed red line in the lake represents the seismic survey line shown in panel **(b)**. Bathymetric lines indicate 10 m increments. **(b)** Seismic reflection profile from the 1995 IDEAL expedition of Lake Victoria (Johnson et al., 1996), with units described in panel **(a)**. **(c)** Regional tephrostratigraphy generated from terrestrial outcrops and from IDEAL lake cores. Modified from Blegen et al. (2021).

mate change. These data will in turn refine our ability to forecast future declines in lake level, which could be catastrophic to human populations in the region (e.g., Beverly et al., 2020; Olaka et al., 2019; Broecker et al., 1998; Milly, 1999). Past interglacials including MIS 5 (130 to 82 ka), MIS 9 (337 to 300 ka) and MIS 11 (424 to 374 ka) are of much scientific interest as they provide insights into the processes and mechanisms of climate change under conditions of elevated warmth. Drilling Lake Victoria will provide new high-resolution records that we hypothesize formed during interglacials from the continental tropics where few such records presently exist. These data will refine our ability to project future major shifts in lake level.

3 Workshop structure and discussions

The LVDP workshop began with opening remarks and introductions, particularly focused on the history of the LVDP and the goal to recover the complete Lake Victoria sedimentary record (currently estimated to cover 400 ka–present, at $\sim$ 60 m length, based on modern sedimentation rates) and the work and operations of ICDP and the Continental Scientific Drilling (CSD) facilities at the University of Minnesota and project partners at the University of Dar es Salaam (UDSM) and TAFIRI. Following brief introductions from the other participants, the rest of the morning and early afternoon of the first workshop day was spent with brief presentations on the modern climatology of the region; a summary of past Victoria coring efforts and seismic surveys; the modern limnology; the hydrology and water balance; the perspective from current terrestrial fieldwork around the lake; chronology and volcanics; the paleoclimatology of the region; and likely synergies, such as with the National Museums of Kenya and the ongoing Olduvai Gorge Coring Project (OGCP).

We ended the first day of the workshop with small group discussions on the strengths of Lake Victoria as a site for future scientific deep drilling. Addressing what makes Lake Victoria a unique drill site, groups highlighted the following items in their presentations:

i. *There is extensive, ongoing research on and understanding of paleosols and sediments present in outcrops around the lake.* There is a unique opportunity at Lake Victoria for the integration of lacustrine and terrestrial records from the basin because these records can be directly linked by shared tephra deposits (Fig. 3).

ii. *Well-studied terrestrial paleoanthropology/paleontology can be precisely tied to lake extent and environmental change.* Lake level fluctuations also appear to be an important mechanism that drove the within-African dispersal of early populations of *H. sapiens* (Tryon et al., 2015). In this case, the paleosols developed on the lacustrine record are not viewed as "gaps" in more continuous data; instead they provide the means to quantify the climate of the region, including the degree of aridity that allowed them to form (e.g., Beverly et al., 2017), and provide a link between archaeological evidence for human behavior and sedimentary evidence for environmental change.

iii. *Lake Victoria is an excellent location to understand floral and faunal evolution with respect to intervals of lake drying and expansion (including the endemic freshwater fish, cichlids).* Particularly important to understand are the periods of lake desiccation and their impact on evolutionary history of the region's flora and fauna, including the central African rainforest and Serengeti ecosystems. Repeated intervals of lake desiccation and expansion likely played an important role in the speciation and adaptive radiation of endemic lake cichlids that dominate the aquatic food web in modern Lake Victoria and are central to debates on tempo and mode in evolution (e.g., Danley et al., 2012; Meier et al., 2017; Verheyen et al., 2003; Muschick et al., 2018).

iv. *The broad, shallow nature of the lake and large surface area to catchment size compared to other African "Great Lakes" provide the potential to better understand the patterns and drivers of drying, critical for this water source and the millions of people that currently depend on it.* Understanding the pattern and drivers of paleosol development is important not just for past responses but also for future projections and water scarcity risks (e.g., Beverly et al., 2020; Olaka et al., 2019). As the largest lake by surface area in Africa, millions of people are dependent on the lake water for life and livelihood.

v. *Lake Victoria, as a large lake situated at the Equator, is an important place to study high- vs. low-latitude climate forcings.* The unique location of Lake Victoria at the Equator, and relatively simple tectonic history that led to the formation of the lake compared to nearby rift lakes (e.g., Renaut and Owen, 2023), suggests that reconstruction of climate over glacial–interglacial cycles may be important to help us examine the relationship between orbital forcing, ice sheet extent, and more regional tropical patterns of climate variability (e.g., Stager et al., 2011). Additionally, how the changing spatial extent and inflows/outflows of Lake Victoria, the source of the White Nile, and the connection to the climate of the Mediterranean region have developed over these time intervals is unknown.

4 LVDP workshop breakout groups

The second day of the workshop focused on breakout discussions by scientific working groups, beginning with a first set of sessions on key scientific questions that could be tackled with scientific drilling at Lake Victoria and a second session that focused on methods necessary to address key questions. These discussions included what additional science activities prior to drilling are needed to best position the LVDP team for success, what the requirements for on-site science activities and drill site locations are, and what other constraints on drilling operations are. Breakout groups consisted of (1) education/outreach/community engagement; (2) geochronology; (3) regional geology and geophysics; (4) paleoclimate/paleoenvironment/biogeochemistry; and (5) paleoecology to modern ecology/paleontology/evolutionary biology/paleoanthropology. Participants were encouraged to mix between groups based on their interests and expertise. Discussions culminated in presentations to all participants and aggregating themes across groups in order to shape our future drilling approach and make sure the widest set of scientific objectives could be met. The following is a summary of the key discussion points about LVDP opportunities from each breakout group.

4.1 Education, outreach, and community engagement

At some point during the workshop, all participants contributed to the education, outreach, and community engagement group, highlighting the central importance these connections and activities have to the entire LVDP. The group discussed what the LVDP could do to support local groups and stakeholders, the project's strengths, what the LVDP could bring to these partnerships, and how we would assess the success of these efforts. Leadership from TAFIRI and UDSM, as well as collaborators from Kenya Marine and Fisheries Research Institute (KMFRI), Tanzania Water Board, and other local agencies, provided critical insights into both the needs and interests of local groups and stakeholders, as well as how best to engage with these communities and assess the project's success in those endeavors. At the broadest scale, this would involve interaction with local stakeholders including managing agencies on the lake, universities, primary/secondary school children, and local communities before, during, and after drilling. Communication of the goals of the project to local communities would help with sustained community support and could involve climate change and longevity of water and fish resources. This is especially critical on Lake Victoria to prevent any loss of livelihood associated with fishing. Communication could be facilitated through fisheries agencies, such as with partners like TAFIRI, but the group discussed the possibility of primary and secondary school students as ambassadors to local community and families. Engagement with primary and secondary school students could come in the form of LVDP-sponsored activities, including citizen science activities that could include data collection following training, debates, or fun competitions (songs or other artistic endeavors). The group also discussed the forms that capacity building associated with the LVDP could take, including but not limited to on-the-ground training programs, visiting researcher and staff exchange, access to equipment to enhance scientific independence, and proposals with local universities to develop collaborative research around themes of joint interest.

4.2 Geochronology

The geochronology breakout group discussed the methodologies and necessary sampling considerations to provide the best possible framework for sediment recovered. A multi-technique approach to chronology for LVDP materials is best, likely occurring at multiple stages in the project. This is particularly important because the Lake Victoria record will sample both intervals of lacustrine sedimentation and paleosols, which likely represent depositional hiatuses in the lacustrine record. Ideally, chronological work begins with an overview of the recovered materials and working alongside sedimentologists to assess changes downcore. Redox changes are important to consider, as they may impact the utility of some proxies, such as ^{10}Be. Additionally, some of the techniques require early core access, so that samples can be taken on relatively undisturbed materials (e.g., luminescence). Further, tephra techniques tie into advances in regional geology and the understanding of volcanic depositional history of the region and how those compositions evolved through time. Tephra techniques will also be a critical tool to link the lake record, and potentially the paleosols within the cores, to terrestrial deposits surrounding the lake. Primary techniques, considered so because of the age range and substrates, include luminescence dating, such as optically stimulated luminescence (OSL), quartz, < 100 ka) and post-infrared–infrared-stimulated luminescence (pIR-IRSL; feldspar, > 100 ka), ^{14}C (< 50 ka), tephra, for correlation of outcrop to lake and dating via fingerprinting and ^{40}Ar $=$ ^{39}Ar (if enough material is available, > 400 ka), and paleomagnetism (polarity stratigraphy and potentially paleomagnetic reversal, relative paleointensity, paleomagnetic secular variations). Secondary techniques, where suitable material may exist, could include ^{10}Be decay, amino acid racemization on small samples, U-series dating on potential carbonates, and orbital tuning. Correlation between existing outcrop, piston core data (Fig. 3c), and newly generated LVDP geochronology may be possible, which would help strengthen the integration between the extensive past work in the region and new LVDP materials recovered.

4.3 Regional geology and geophysics

The regional geology and geophysics group focused on how the LVDP could help resolve long-standing questions about basin formation, sedimentation, tectonics, and volcanism in the region. From both the recovery of sediment cores, as well as interrogation of new and legacy geophysical data of the lake, the LVDP will address questions about how much sediment is present in the basin, the provenance of that sediment, and how this input has changed through time. The region is relatively tectonically quiescent compared to elsewhere in the rift system, and prior geophysical surveys found laterally continuous sediments (Fig. 3b) (Johnson et al., 1996; Scholz et al., 1998). The project could assess if recovered cores capture a record of seismicity and, with a better understanding of the tectono-sedimentary history of Lake Victoria, the possibility of rapidly shifting depocenters. The LVDP data would provide an opportunity to determine marginal uplift rates and the possibility to develop a detailed history of changing inflows and outflows to the lake and determine how those changes have impacted lake stratigraphy. Ultimately, we would incorporate the existing drainage networks with the history of rift shoulder uplift and seismic stratigraphic sequence and facies architecture to aid in our understanding of hydroclimate evolution of Lake Victoria. Results from the geophysical surveys and cores would be integrated with outcrop data from around the lake to better understand the regional geology and depositional history of the lake both when it was and was not present.

4.4 Paleoclimate, paleoenvironment, and biogeochemistry

This breakout group focused on how the LVDP would contribute to our understanding of paleoclimate and paleoenvironmental change in the region and associated biogeochemical changes within the lake that may be linked to terrestrial and atmospheric variability. Specifically, we would examine the drivers of climate change, looking at the role of high-latitude processes, such as ice sheet expansion or deglacial melting, in atmospheric circulation vs. low-latitude drivers, such as Indian or Atlantic Ocean changes in sea surface temperature. The lake is a sensitive recorder of desiccation and refilling, as interpreted from outcrop and existing geophysical survey data. Desiccation events are likely represented by paleosols within the lake record, which can potentially be correlated to terrestrial outcrops surrounding the modern lake. One of the major outstanding questions about the paleoclimate and paleoenvironmental history is as follows: what controlled these desiccation events? Whether each drying of the lake was due to the same driver or different regional and/or global climate drivers, the potential role that basinal tilting played, and whether desiccation and refilling events occur with some repeating cyclicity, will be investigated. Lake Victoria's connection to the Nile would allow us to compare a history of lake level changes with Nile runoff and, ultimately, changes around the Mediterranean Sea. Correlations between the lake cores and terrestrial deposits in the region would provide critical insights into the connection between lake level change and regional climate. Proxy reconstructions from a complete sedimentary record recovered from Lake Victoria would allow us to address questions of similarity to records elsewhere in Africa and provide an invaluable means of creating a high-resolution regional picture of climate and environmental change. This, in turn, would be used to better frame the extensive archaeological record around the region.

4.5 Paleoecology to modern ecology, paleontology, and evolutionary biology

The modern to paleoecological systems group focused on how to best integrate our understanding of modern Lake Victoria and surrounding basins with reconstructions of aquatic flora and fauna from various paleoproxies. Ideally, this would involve examining the connection between modern aquatic communities and ancient communities by trophic levels, evolutionary lineages, and understanding extinction of modern aquatic taxa. As part of the modern conditions informing the past, the group discussed how to leverage LVDP to advance existing and establish new regional modern observational studies and build partnerships with the agencies studying the lake and associated systems. The group discussed how the LVDP could examine questions of the evolution and rates (protracted vs. punctuated) of changes in fish populations (both native cichlids in the lake and introduced Nile perch, depending on core material recovered) and impacts of the changing environment and climate on these populations through time. Questions related to the causes and possible recurrence of shifting algae and other microbiota through time could be addressed, such as the shift in dominant phytoplankton and possible connection to changing fish populations. Understanding the hydrological connection to other lakes and rivers across the region, and how and when drainage changes may have occurred, will allow us to examine questions surrounding the impact of migration corridors for both aquatic and terrestrial fauna.

5 Logistics

The final day of the workshop focused on discussions about logistics and site selection to meet the goal of recovering the complete sedimentary record of Lake Victoria), including recovering sediments and paleosols below those recovered in 1995 (>15 ka, ~ 6 m) (Johnson et al., 1996). Based on modern sedimentation rate estimates, the complete record is estimated to span ~ 400 kyr and be ~ 60 m in length. Existing seismic data, which are currently being reprocessed using modern techniques, and newly acquired high-resolution seismic data will need to be leveraged to determine the optimal drill sites. Based on existing data, the group determined that drilling in one geographic location would likely recover the lake's complete record. Further, the group advised that the site be chosen based on a combination of the longest possible sedimentary record and the least disturbed uppermost section (from sedimentary gas accumulation), while considering access to the site and onshore mobilization.

Site selection discussions at the time of the LVDP workshop were based on geophysical surveys from the 1980s and 1990s (Fig. 3b). The NSF-funded 1995 IDEAL expedition collected nearly 2000 km of seismic reflection profiles using a 16.4 cc (1 in.^{3}) airgun (Scholz et al., 1998). Additionally, profiles were gathered from the 1985 Project PROBE survey, which collected multichannel seismic reflection data using a 2300 cc (140 in.^{3}) seismic source (e.g., Rach and Rosendahl, 1989). However, coincident with the start of the LVDP workshop, a new, high-resolution geophysical survey of Lake Victoria was funded in 2022 by the National Science Foundation (NSF) and led by Christopher Scholz and in partnership with TAFIRI, in order to examine more of the lake's depositional history and optimize drilling locations. The survey, following meetings with TAFIRI scientists including Mary Kishe (Director of Research and Coordination) and Baraka Sekadende (Centre Director, Mwanza), was completed in Tanzanian waters (e.g., areas south of 1° S latitude) in January 2023 and used CHIRP (Compressed High Intensity Radiated Pulse) seismic reflection using an Edgetech 3200 XS profiler and SB-0512 towfish system. The modern CHIRP high-resolution profiles are coincident with the legacy 1995 and 1985 multichannel seismic data acquired using an airgun source. This reprocessed legacy multichannel data and new CHIRP data will be integrated to assess the fine-scale structural and stratigraphic framework across the basin and select the optimal site for drilling. Processing of data will continue through 2023, providing a better understanding of the sedimentary package and site selection by the end of the year. Additionally, an environmental impact assessment and sensitization campaigns around local communities, particularly with regards to any possible short-term fishery disruptions, need to occur early in project development.

6 Workshop conclusions and next steps

Discussions by multidisciplinary scientists and regional stakeholders showed that broad interest and significance in the LVDP focused around (1) lacustrine basin formation and development, (2) tropical climate and environmental change over multiple glacial–interglacial cycles, (3) climate linkages to lake desiccation events, (4) diversification and evolution of aquatic fauna responding to lake dynamics and climate change, (5) climate and environmental pressures associated with lake extent driving dispersal of early human and animal populations, and (6) savanna ecosystem changes and their biogeographic implications. The LVDP offers this unique combination of research opportunities while also being highly complementary to lake drilling efforts elsewhere in eastern Africa. The LVDP team researchers (see below), made up of those attending the ICDP workshop July 2022, who have contributed to the LVDP since its earliest development, and those who have expressed an interest in the science and operations at Lake Victoria, will continue conversations and planning for the next steps of this project.

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

Team list. Patrick Andrews (University of Texas, Austin, USA), Simon Armitage (Royal Holloway University of London, UK), Catherine Beck (Hamilton College, USA), Melissa A. Berke (University of Notre Dame, USA), Emily Beverly (University of Houston, USA), Cécile Blanchet (GFZ Potsdam, Germany), Simon Brassell (Indiana University Bloomington/Stone Age Institute, USA), Mariam Bundala (University of Dar es Salaam, Tanzania/University of Calgary, Canada), Kat Cantner (University of Minnesota/CSD Facility, USA), Isla Castañeda (University of Massachusetts Amherst, USA), Leon Clarke (Manchester Metropolitan University, UK), Kerry Cook (University of Texas, Austin, USA), Sara Emanuel (University of Dar es Salaam, Tanzania), John Tyler Faith (Natural History Museum of Utah/University of Utah, USA), Karen Fontijn (Université Libre de Bruxelles, Belgium), Martin Grosjean (University of Bern, Switzerland), Thomas Johnson (University of Massachusetts Amherst, USA), Claudia Johnson (Indiana University Bloomington, USA), Edmund Kajuni (Tanzania Fisheries Research Institute, Tanzania), Tumaini Kamulali (University of Arizona, USA/Tanzania Fisheries Research Institute, Tanzania), Charles Kasanzu (University of Dar es Salaam, Tanzania), Benedicto Kashindye (Tanzania Fisheries Research Institute, Tanzania), Emmanuel Kazimoto (University of Dar es Salaam, Tanzania), Jackson Kimambo (Wits University, South Africa), Ismael Kimirei (Tanzania Fisheries Research Institute, Tanzania), Rahab Kinyanjui (National Museums of Kenya, KE), Emmanuel Kisendi (Ministry of Water, Tanzania), Mary Kishe (Tanzania Fisheries Research Institute, Tanzania), Emily Kiswaka (University of Dar es Salaam, Tanzania), Sifan A. Koriche (Baylor University, USA), Christine Lane (University of Cambridge, UK), Muyo Machaule (University of Dar Es Salaam, Tanzania), Patrick Machumu (Tanzania Mining Commission, Tanzania), Stephen Peter Magohe (University of Dar es Salaam, Tanzania/University of Calgary, Canada), Marta Marchegiano (Vrije Universiteit Brussels, Belgium/University of Granada, ESP), Mbushi Charles Mbushi (University of Dodoma, Tanzania), Dhelda Mfanga (University of Dar es Salaam, Tanzania), Fred Mkuyi (University of Dar es Salaam, Tanzania), Elisante Mshiu (University of Dar es Salaam, Tanzania), Veronica Muiruri (National Museums of Kenya, KE), Moritz Muschick (University of Bern, Switzerland), Amy Myrbo (Amiable Consulting, USA), Hillary Mwongyera (University of Kansas, USA), Erick Ngaratoki (University of Dodoma, Tanzania), Elizabeth Niespolo (Princeton University, USA), Lambert Niyoyitungiye (University of Burundi, Burundi), Hope Yisi Mofor Njakoi (Tanzania Geological Society, Tanzania), Jackson Njau (Indiana University Bloomington/Stone Age Institute, USA), Anders Noren (University of Minnesota/CSD Facility, USA), Julian Ogondo (Maseno University, KE), Daniel Olago (University of Nairobi, KE), Lekeni Olle Moita (Syracuse University, USA), Collins Ongore (Kenya Marine and Fisheries Research Institute, KE/St Andrews University, UK), Daniel J. Peppe (Baylor University, USA), Simona Pierdominici (GFZ Potsdam, Germany), Nathan Rabideaux (Rutgers University Newark, USA), Violka Radmacher (Polish Academy of Sciences, Poland), Adam Renatus (Lake Victoria Basin Water Board, Tanzania), Mohamed Said (School of Mines and Geosciences, Tanzania), Salome Sharon (Tanzania Fisheries Research Institute, Tanzania), Kathy Schick (Indiana University Bloomington/Stone Age Institute, USA), Chris Scholz (Syracuse University, USA), Antje Schwalb (TU Braunschweig, Germany), Ole Seehausen (EAWAG, Switzerland), Baraka Sekadende (Tanzania Fisheries Research Institute, Tanzania), Mark Sier (CENIEH, Spain), Majura Sonogo (University of Dar es Salaam, Tanzania), Charlotte Spencer-Jones (Durham University, UK), Ian Stanistreet (University of Liverpool, UK/Stone Age Institute, USA), Harald Stollhofen (Friedrich-Alexander University Erlangen Nürnberg, Germany/Stone Age Institute, USA), Nicholas Toth (Indiana University Bloomington/Stone Age Institute, USA), Christian Tryon (University of Connecticut, USA), Edward Vizy (University of Texas, Austin, USA), Hendrik Vogel (University of Bern, Switzerland), Christian Zeeden (Leibniz Institute for Applied Geophysics, Germany), and Boyang Zhao (Brown University, USA).

Author contributions. MAB and DJP wrote the manuscript. All members of the LVDP team read the paper, provided feedback, and approved the final version.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. We would like to thank the Tanzania Fisheries Research Institute and the University of Dar es Salaam for logistical assistance in Tanzania; recommendations for the workshop location; and engaged participation and collaboration before, during, and after the workshop.

Financial support. The workshop was supported by the International Continental Scientific Drilling Program.

Review statement. This paper was edited by Tomoaki Morishita and reviewed by two anonymous referees.

References

Awange, J. L., Saleem, A., Sukhadiya, R. M., Ouma, Y. O., and Kexiang, H.: Physical dynamics of Lake Victoria over the past 34 years (1984–2018): Is the lake dying?, Sci. Total Environ., 658, 199–218, https://doi.org/10.1016/j.scitotenv.2018.12.051, 2019.

Berke, M. A., Johnson, T. C., Werne, J. P. Grice, K., Schouten, S., and Sinninghe Damsté, J. S.: Molecular records of climate variability and vegetation response since the Late Pleistocene in the Lake Victoria basin, East Africa, Quat. Sci. Rev., 55, 59–74, https://doi.org/10.1016/j.quascirev.2012.08.014, 2012.

Beverly, E. J., Peppe, D. J., Driese, S. G., Blegen, N., Faith, J. T., Tryon, C. A., and Stinchcomb, G. E.: Reconstruction of Late Pleistocene paleoenvironments using bulk geochemistry of paleosols from the Lake Victoria region, Front. Earth Sci., 5, https://doi.org/10.3389/feart.2017.00093, 2017.

Beverly, E. J., White, J. D., Peppe, D. J., Faith, J. T., Blegen, N., and Tryon, C. A.: Rapid Pleistocene desiccation and the future of Africa's Lake Victoria, Earth Planet. Sc. Lett., 530, 115883, https://doi.org/10.1016/j.epsl.2019.115883, 2020.

Bishop, W. W.: Pleistocene stratigraphy in Uganda, Geo. Survey of Uganda Mem. X, 1969.

Bishop, W. W. and Posnansky, M.: Pleistocene environments and early man in Uganda, Uganda J., 24, 44–61, 1960.

Bishop, W. W. and Trendall, A. F.: Erosion surfaces, tectonics, and volcanic activity in Uganda, Quart. J. Geo. Soc. Lon., 122, 385–420, 1966.

Blegen, N., Faith, J. T., and Peppe, D. J.: Tephrostratigraphy of the eastern Lake Victoria Basin including the Nyanza Rift, Kenya: building a stratigraphic and chronological framework for modern human evolution, Quaternary Sci. Rev., 256, 106823, https://doi.org/10.1016/j.quascirev.2021.106823, 2021.

Broecker, W. S., Peteet, D., Hajdas, I., Lin, J., and Clark, E.: Antiphasing between rainfall in Africa's Rift Valley and North America's Great Basin, Quaternary Res., 50, 12–20, https://doi.org/10.1006/qres.1998.1973, 1998.

Cohen, A. S., Scholz, C. A., and Johnson, T. C.: The International Decade of East African Lakes (IDEAL) drilling initiative for the African great lakes, J. Paleolim., 24, 231–235, https://doi.org/10.1023/A:1008158902422, 2000.

Danley, P. D., Husemann, M., Ding, B., Dipietro, L. M., Beverly, E. J., and Peppe, D. J.: The impact of the geologic history and paleoclimate on the diversification of East African cichlids, Int. J. Evo. Bio., 2012, 574851, https://doi.org/10.1155/2012/574851, 2012.

Faith, J. T., Tryon, C. A., Peppe, D. J., and Fox, D. L.: The fossil history of Grévy's zebra (*Equus grevyi*) in equatorial East Africa, J. Biog., 40, 359–369, https://doi.org/10.1111/j.1365-2699.2012.02796.x, 2013.

Faith, J. T., Tryon, C. A., Peppe, D. J., Beverly, E. J., and Blegen, N.: Biogeographic and Evolutionary Implications of an Extinct Late Pleistocene Impala from the Lake Victoria Basin, Kenya, J. Mamm. Evol., 21, 213–222, https://doi.org/10.1007/s10914-013-9238-1, 2014.

Faith, J. T., Tryon, C. A., and Peppe, D. J.: Environmental change, ungulate biogeography, and their implications for early human dispersals in equatorial East Africa, in: Africa from MIS 6-2: Population Dynamics and Paleoenvironments, edited by: Jones, S. C. and Stewart, B. A., Springer, Dordrecht, 233–245, https://doi.org/10.1007/978-94-017-7520-5_13, 2016.

Flohn, H. and Burkhardt, T.: Nile runoff at Aswan and Lake Victoria: a case of a discontinuous climate time series, Zeits. Gletsch. Glaz., 21, 125–130, 1985.

Herrmann, S. M. and Mohr, K. I.: A continental-scale classification of rainfall seasonality regimes in Africa based on gridded precipitation and land surface temperature products, J. Appl. Meteorol. Clim., 50, 2504–2513, https://doi.org/10.1175/JAMC-D-11-024.1, 2011.

Johnson, T. C.: International Decade of East African Lakes, Eos T. Am. Geophys. Un., 72, 258–259, https://doi.org/10.1029/90EO00198, 1991.

Johnson, T. C., Scholz, C. A., Talbot, M. R., Kelts, K., Ricketts, R. D., Ngobi, G., Beuning, K., Ssemmanda, I., and McGill, J. W.: Late Pleistocene desiccation of Lake Victoria and rapid evolution of cichlid fishes, Science, 273, 1091–1093, https://doi.org/10.1126/science.273.5278.1091, 1996.

Kent, P. E.: The country round the Kavirondo Gulf of Victoria Nyanza, Geog. J., 100, 22–31, https://doi.org/10.2307/1789231, 1942.

Kingdon, J., Happold, D., Butynski, T., Hoffman, M., and Kalina, J.: Mammals of Africa (Vol. I–VI), Bloomsbury Publishing, London, ISBN 9781408189962, 2013.

Meier, J. I., Marques, D. A., Mwaiko, S., Wagner, C. E., Excoffier, L., and Seehausen, O.: Ancient hybridization fuels rapid cichlid fish adaptive radiations, Nat. Commun., 8, 14363, https://doi.org/10.1038/ncomms14363, 2017.

Milly, P. C. D.: Comment on "Antiphasing between Rainfall in Africa's Rift Valley and North America's Great Basin", Quaternay Res., 51, 104–107, https://doi.org/10.1006/qres.1998.2011, 1999.

Muschick, M., Russell, J. M., Jemmi, E., Walker, J., Stewart, K. M., Murray, A. M., Dubois, N., Stager, J. C., Johnson, T. C., and Seehausen, O.: Arrival order and release from competition does not explain why haplochromine cichlids radiated in Lake Victoria, Philos. T. Roy. Soc. B., 285, ISSN 1471-2954, https://doi.org/10.1098/rspb.2018.0462, 2018.

Mutai, C. C. and Ward, M. N.: East African rainfall and the tropical circulation/convection on intraseasonal to interannual timescales, J. Climate, 13, 3915–3939, https://doi.org/10.1175/1520-0442(2000)013<3915:EARATT>2.0.CO;2, 2000.

Nicholson, S. E.: The Turkana low-level jet: mean climatology and association with regional aridity, Int. J. Climatol., 36, 2598–2614, https://doi.org/10.1002/joc.4515, 2016.

Ogallo, L. J. and Janowiak, J. E.: Teleconnection between seasonal rainfall over East Africa and global sea surface temperature anomalies, J. Meteorol. Soc. Jpn. Ser. II, 66, 807–822, https://doi.org/10.2151/jmsj1965.66.6_807, 1988.

Ogondo, J., Oindo, B., Olago, D. O., and Woodborne, S.: Bulk sediment geochemistry, a proxy palaeowater quality indicator of the Mid-Late Pleistocene beaches of Rusinga-Mfangano Islands, Lake Victoria, Kenya, Maseno Uni. Jour., 1, 65–81, https://www.maseno.ac.ke/sites/default/files/2022-05/MASENO UNIVERSITY JOURNAL Volume 1-2022-18-Apr-2022-Collins-Final.pdf (last access: August 2023), 2022.

Olaka, L. A., Ogutu, J. O., Said, M. Y., and Oludhe, C.: Projected Climatic and Hydrologic Changes to Lake Victoria Basin Rivers under Three RCP Emission Scenarios for 2015–2100 and Impacts on the Water Sector, Water, 11, 1449, https://doi.org/10.3390/w11071449, 2019.

Otto-Bliesner, B. L., Russell, J. M., Clark, P. U., Liu, Z., Overpeck, J. T., Konecky, B., deMenocal, P., Nicholson, S. E., He, F., and Lu, Z.: Coherent changes of southeastern equatorial and northern African rainfall during the last deglaciation, Science 346, 1223-1227, https://doi.org/10.1126/science.1259531, 2014.

Rach, N. M. and Rosendahl, B. R.: Tectonic controls on the Speke Gulf, J. Afr. Ear. Sci. (and the Middle East), 8, 471–488, https://doi.org/10.1016/S0899-5362(89)80040-5, 1989.

Renaut, R. W. and Owen, R. B.: Lake Victoria Basin, in: The Kenya Rift Lakes: Modern and Ancient: Limnology and Limnogeology of Tropical Lakes in a Continental Rift, Springer Berlin Heidelberg, Berlin, Heidelberg, 883–905, ISBN 3-642-25054-8, 2023.

Scholz, C. A., Johnson, T. C., Cattaneo, P., Malinga, H., and Shana, S.: Environmental Change and Response in East African Lakes, edited by: Lehman, J. T., Springer, 47–58, https://doi.org/10.1007/978-94-017-1437-2, 1998.

Seehausen, O.: Lake Victoria Rock Cichlids: taxonomy, ecology, and distribution, Verduijn Cichlids, Zevenhuizen, the Netherlands, ISBN 9789080018167, 1996.

Smith, K. A. and Semazzi, F. H. M.: The role of dominant modes of precipitation variability over Eastern Africa in modulating the hydrology of Lake Victoria, Adv. Meteorol., 2014, 516762, https://doi.org/10.1155/2014/516762, 2014.

Stager, J. C., Mayewski, P. A., and Meeker, L. D.: Cooling cycles, Heinrich event 1, and the desiccation of Lake Victoria, Palaeogeogr. Palaeocl., 183, 169–178, https://doi.org/10.1016/S0031-0182(01)00468-0, 2002.

Stager, J. C., Ryves, D. B., Chase, B. M., and Pausata, F. S. R.: Catastrophic Drought in the Afro-Asian Monsoon Region During Heinrich Event 1, Science, 331, 1299–1302, https://doi.org/10.1126/science.1198322, 2011.

Talbot, M. R. and Laerdal, T.: The Late Pleistocene-Holocene paleolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary organic matter, J. Paleolimnol., 23, 141–164, https://doi.org/10.1023/A:1008029400463, 2000.

Tate, E., Sutcliffe, J., Conway, D., and Farquharson, F.: Water balance of Lake Victoria: Update to 2000 and climate change modeling to 2100, Hydrolog. Sci. J., 49, 563–574, https://doi.org/10.1623/hysj.49.4.563.54422, 2004.

Temple, P. H. and Doornkamp, J. C.: Influences controlling lacustrine overlap along the north-western margins of Lake Victoria, Z. Geomorphol., 14, 301–317, 1970.

Thiery, W., Martynov, A., Darchambeau, F., Descy, J.-P., Plisnier, P.-D., Sushama, L., and van Lipzig, N. P. M.: Understanding the performance of the FLake model over two African Great Lakes, Geosci. Model Dev., 7, 317–337, https://doi.org/10.5194/gmd-7-317-2014, 2014.

Tryon, C. A. and Faith, J. T.: Variability in the Middle Stone Age of Eastern Africa, Curr. Anthropol., 54, S234–S254, https://doi.org/10.1086/673752, 2013.

Tryon, C. A., Faith, J. T., Peppe, D. J., Beverly, E. J., Blegen, N., Blumenthal, S. A., Chritz, K. L., Driese, S. G., Patterson, D., and Sharp, W. D.: The Pleistocene prehistory of the Lake Victoria basin, Quatern. Int., 404, 100–114, https://doi.org/10.1016/j.quaint.2015.11.073, 2015.

Vanderkelen, I., van Lipzig, N. P. M., and Thiery, W.: Modelling the water balance of Lake Victoria (East Africa) – Part 2: Future projections, Hydrol. Earth Syst. Sci., 22, 5527–5549, https://doi.org/10.5194/hess-22-5527-2018, 2018.

Verheyen, E., Salzburger, W., Snoeks, J., and Meyer, A.: Origin of the Superflock of Cichlid Fishes from Lake Victoria, East Africa, Science, 300, 325–329, https://doi.org/10.1126/science.1080699, 2003.

Vizy, E. K. and Cook, K. H.: Interannual variability of East African rainfall: Role of seasonal transitions of the low-level cross-equatorial flow, Clim. Dynam., 54, 4563–4587, https://doi.org/10.1007/s00382-020-05244-z, 2020.

Yang, W., Seager, R., Cane, M. A., and Lyon, B.: The annual cycle of East African precipitation, J. Climate, 28, 2385–2404, https://doi.org/10.1175/JCLI-D-14-00484.1, 2015.

Yin, X. and Nicholson, S. E.: Interpreting annual rainfall from the levels of Lake Victoria, J. Hydrometeorol., 3, 406–416, https://doi.org/10.1175/1525-7541(2002)003<0406:IARFTL>2.0.CO;2, 2002.

Sci. Dril., 33, 33–46, 2024
https://doi.org/10.5194/sd-33-33-2024
© Author(s) 2024. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

Workshop Reports

NorthGreen: unlocking records from sea to land in Northeast Greenland

Lara F. Pérez[1], **Paul C. Knutz**[1], **John R. Hopper**[2], **Marit-Solveig Seidenkrantz**[3], **Matt O'Regan**[4], and **Stephen Jones**[5]

[1]Department of Near-surface Land and Marine Geology, Geological Survey of Denmark and Greenland, Aarhus University City 81, 1872, 8000 Aarhus, Denmark
[2]Department of Geophysics and Sedimentary Basins, Geological Survey of Denmark and Greenland, Øster Volgade 10, 1350 Copenhagen, Denmark
[3]Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, 672–213, 8000 Aarhus, Denmark
[4]Department of Geological Sciences, Stockholm University, Svante Arrheniusväg 8C, R223, 10691 Stockholm, Sweden
[5]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

Correspondence: Lara F. Pérez (lfp@geus.dk)

Received: 24 July 2023 – Revised: 14 December 2023 – Accepted: 23 December 2023 – Published: 2 April 2024

Abstract. The increasing anthropogenic CO_2 forcing of the climate system calls for a better understanding of how polar ice sheets may respond to accelerating global warming. The sensitivity of the Greenland ice sheet to polar amplification, changes in ocean heat transport, and deteriorating perennial sea ice conditions makes the Northeast Greenland margin a pertinent location with respect to understanding the impact of climate change on ice sheet instability and associated sea level rise. Throughout the Cenozoic, ocean heat fluxes toward and along Northeast Greenland have been controlled by water mass exchanges between the Arctic and Atlantic oceans. A key element here is the current flow through oceanic gateways, notably the Fram Strait and the Greenland–Scotland Ridge. To gain a long-term (million-year) perspective of ice sheet variability in this region, it is essential to understand the broader context of ice–ocean–tectonic interactions. Coupling between the ice sheet, the subsurface, the ocean, and sea ice are readily observable today in Northeast Greenland, but geological records to illuminate long-term trends and their interplay with other parts of the global climate system are lacking. Consequently, the NorthGreen workshop was organized by the Geological Survey of Denmark and Greenland in collaboration with Aarhus (Denmark) and Stockholm (Sweden) universities in November 2022 to develop mission-specific platform (MSP) proposals for drilling the Northeast Greenland margin under the umbrella of the MagellanPlus Workshop Series Programme of the European Consortium for Ocean Research Drilling (ECORD). Seventy-one participants representing a broad scientific community discussed key scientific questions and primary targets that could be addressed through scientific drilling in Northeast Greenland. Three pre-proposals were initiated during the workshop targeting Morris Jesup Rise, the Northeast Greenland continental shelf, and Denmark Strait.

1 Introduction

The Greenland ice sheet is $\sim 1.7 \times 10^6$ km^2 with a maximum thickness of 3 km. During the past few decades, it has been a major contributor to global sea level rise (van den Broeke et al., 2016; Shepherd et al., 2020; Christ et al., 2023), and if melted completely, the Greenland ice sheet would represent a sea level rise equivalent to ~ 7.5 m (e.g., Dutton et al., 2015; Morlighem et al., 2017). Numerical models suggest a present negative ice mass balance and a marked increase in ice sheet runoff as a consequence of polar amplification in the Arctic (Rignot et al., 2011; Golledge et al., 2019; Hofer et al., 2020). In addition, sea ice cover in the Arctic Ocean has substantially shrunk over the last few years, with ice models suggesting a high probability of an ice-free Arctic Ocean in late summer by 2050 (Notz and SIMIP Community, 2020). However, predictive models on extended time frames are often working outside of the limits in which they have demonstrable skill. The projections of future scenarios under the current trend of global climate change demand a better understanding of long-term ice–ocean–tectonic interactions (IPCC, 2019). This broad achievement requires access to paleodata that are hidden in the sedimentary successions of polar margins.

Antarctic and Southern Ocean marine sediments have been recovered on seven scientific drilling expeditions under the framework of the International Ocean Discovery Program (IODP) and its predecessors. These Cenozoic marine sediment archives have significantly contributed to the understanding of the sensitivity of the Antarctic ice sheet to elevated global temperatures and greenhouse gas concentrations (Escutia et al., 2019). However, scientific drilling expeditions in the Arctic and northern North Atlantic oceans have, until now, focused on sites far from the Greenland margins (Fig. 1), e.g., Ocean Drilling Program (ODP) 151, IODP 395, and IODP 302 (Arctic Coring Expedition – ACEX) as well as the scheduled IODP Expedition 403 to the eastern Fram Strait (Lucchi et al., 2023). The hitherto only drilling campaign directly targeting Greenland margin sedimentary successions has been IODP Expedition 400, implemented in 2023, which has investigated the glacial–interglacial variability and late-Cenozoic paleoceanography of the Northwest Greenland margin (Knutz et al., 2024). Thus, the Northeast Greenland glaciation history remains a major knowledge gap, hampering understanding of the influence of the Greenland ice sheet on future climate projections and of its sensitivity to a warmer-than-present climate. The aim of this work is to provide a general overview of the recent activities to foster scientific drilling in the Northeast Greenland Margin, based on the long-term research strategy discussed during the NorthGreen MagellanPlus workshop.

2 Scientific background: tectonics, oceanography, and cryosphere in Northeast Greenland

The Northeast Greenland margin experienced a long history of rifting prior to the onset of the continental breakup and oceanic spreading during the Paleocene–Eocene transition (e.g., Talwani and Eldholm, 1977; Hamann et al., 2005; Gaina et al., 2017). The post-breakup sedimentary record varies in thickness along the margin and comprises thick sedimentary wedges deposited during distinct phases of Neogene uplift (e.g., Hamann et al., 2005; Berger and Jokat, 2008, 2009; Tsikalas et al., 2012). However, glaciation-related processes have also left imprints on the margin's sedimentary sequences, recording the variability in sea ice, ice sheets, ice shelves, and glaciers on seasonal, interannual, and glacial–interglacial timescales. Evidence of a glaciated hinterland and the presence of tidewater glaciers in Greenland extends back to Eocene–Miocene times (e.g., Solheim et al., 1998; Tripati et al., 2008; Thiede et al., 2010). A permanent Greenland ice sheet was formed during the middle Miocene (Larsen et al., 1994; St. John and Krissek, 2002; Berger and Jokat, 2008, 2009; Thiede et al., 2010), eventually prograding asynchronously over the continental shelves (Døssing et al., 2016; Pérez et al., 2018; Heirman et al., 2019). The subsequent glacial history of Greenland has been marked by the dynamic behavior of the ice sheet, with several pulses of glacial intensification at 7, 2.8, 1.9, and 0.8 Ma (Larsen et al., 1994; Solheim et al., 1998; St. John and Krissek, 2002; Bierman et al., 2016). During periods of maximum ice sheet advance, trough-mouth fans formed at the paleo continental shelf edge as thick, prograding wedges of sediments delivered by the cross-shelf flow of ice streams (e.g., Pérez et al., 2018). The ice streams in Northeast Greenland are highly sensitive to warm climate periods. For example, the Northeast Greenland ice stream retreated up to 70 km behind its present-day extent during Quaternary periods of high orbital precession index and summer temperatures (Larsen et al., 2018).

Ice sheet dynamics in Greenland have been influenced by the variability in oceanographic patterns and, therefore, the opening and deepening of oceanic gateways (Smith and Pickering, 2003). The opening of the Fram Strait resulted in the onset of the modern, ventilated Arctic Ocean with the exchange of water masses with the northern North Atlantic Ocean (Jakobsson et al., 2007; Rudels, 2009). The timing of gateway formation is still debated (e.g., Engen et al., 2008; Ehlers and Jokat, 2013; Jokat et al., 2015), but outflow of cold water from the Arctic Ocean to the northern North Atlantic Ocean through the Fram Strait is generally thought to coincide with the onset of the East Greenland Current (EGC) during the late Miocene (Wolf and Thiede, 1991; Våge et al., 2013) or early Pliocene (De Schepper et al., 2015; Clotten et al., 2019). The southern flow of the EGC was also controlled by the opening of the Denmark Strait during the Miocene, although the more precise timing is debated, and subsequently

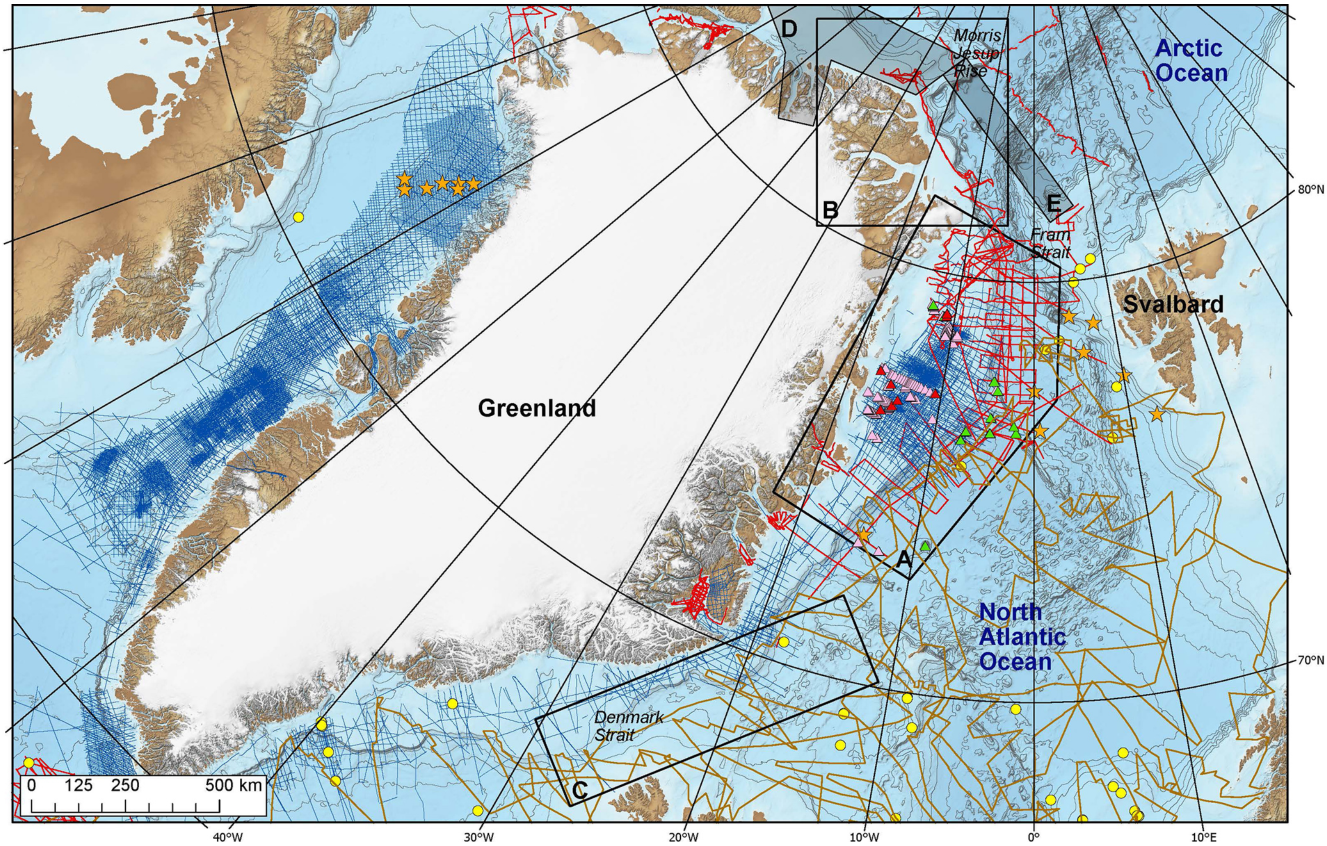


Figure 1. Greenland margin's bathymetry map from the GEBCO_2019 grid (http://www.gebco.net, last access: 24 July 2023) showing the available data as follows: blue lines – commercial seismic reflection data available at the Geological Survey of Denmark and Greenland (GEUS); red lines – other seismic reflection data available from academic data owners; brown lines – single-channel seismic data; yellow dots – existing Deep Sea Drilling Project (DSDP) and ODP drill sites; orange stars – proposed IODP drill sites with JOIDES Resolution Facility Board (JRFB); red triangles – Kanumas Consortium 2008 cores; pink triangles – other industry gravity cores; and green triangles – industry dredges. Cores only reaching through the Holocene are not shown. A, B, and C denote areas of interest for the NorthGreen MagellanPlus workshop; D and E denote GEOEO and GoNorth planned expeditions in 2024.

influenced by the dynamic topography along the Greenland–Scotland Ridge in response to pulsing of the Iceland plume (White et al., 1995; Wright and Miller, 1996; Poore et al., 2006; Engen et al., 2008; Parnell-Turner et al., 2015). Major pre-Quaternary changes in the EGC are recorded by contourite deposits on the slopes of East Greenland (e.g., Davies et al., 2021). On the continental shelf, warm and saline water of Atlantic origin, the Atlantic Intermediate Water (AIW), enters major troughs (Budéus and Schneider, 1995) while Submarine Melt Water (SMW) flows eastwards to the deep basins, transforming the Atlantic Meridional Overturning Circulation (AMOC) (Böning et al., 2016).

3 Workshop scope and objectives

A large portion of the aforementioned paleoclimate history is supported by data and samples from the Ocean Drilling Program (ODP) Expedition 151 and Expedition 162 in the central North Atlantic Ocean (Jansen et al., 1996; Thiede et al., 1996). However, the Northeast Greenland margin represents a major knowledge gap in the Cenozoic climatic–oceanographic–tectonic evolution of Earth, and key scientific uncertainties remain with respect to three major topics: sea ice history, Greenland ice sheet evolution, and oceanic gateways. With respect to sea ice history, the following question remains: "When did a perennial sea ice cover develop in the Arctic Ocean, and how often did sea-ice-free conditions occur?". Regarding Greenland ice sheet evolution, the following questions are put forward: "When did glaciation in Greenland begin, and how did the ice sheet evolve over the Cenozoic?", "Did past warm climates (e.g., super-interglacials, Eemian) cause whole or partial deglaciation in Northern Greenland (Schaefer et al., 2016; Christ et al., 2023)?", and "Alternatively, is glaciation of Northeast Greenland a relatively pervasive feature in the climate system, with the ice sheet being preserved during peak warmings (Bierman et al., 2016)?". Finally, with respect to oceanic gateways, the following questions remain: "What is the timing and progression of the opening of Fram Strait?", "What is the subsidence history of the conjugate Morris Jesup Rise and Yermak Plateau?", "How did their formation and subsidence influence the oceanographic development of the Arctic Ocean from isolated to fully ventilated (Jakobsson et al., 2007; Poirier and Hillaire-Marcel, 2011)?", and "When did the Denmark Strait open, how was its cross-sectional area subsequently influenced by Icelandic mantle plume activity, and what were the relative roles of gateway tectonics and ice sheet/sea ice evolution in controlling the AMOC?".

Paleorecords proximal to Greenland and across the land–ocean boundary can address these fundamental questions that have far-reaching implications for our understanding of how the climate system operates now as well as how it operated in the past. Data required to illuminate these questions are potentially contained in the sedimentary successions offshore and onshore in Northeast Greenland (Bennike et al., 2002, 2010). While harsh environmental conditions have limited the geophysical data acquisition needed to define drilling targets, data collection in these remote and ice-filled waters has increased substantially over the last 2 decades. The Atlantic margin of Northeast Greenland (Area A in Fig. 1) is now well covered by high-quality industry seismic data (Christiansen, 2021). In addition, the collection of shallow seismic data, gravity cores, and shallow industry boreholes demonstrates the possibility of mission-specific platform (MSP) operations. Hence, sufficient data are available to start developing a MSP proposal on the northeastern continental shelf (Area A). Although far less explored, new seismic data from icebreaker-led expeditions to the Arctic margin of North and Northeast Greenland (Area B in Fig. 1) as well as novel approaches to data collection from drifting ice stations (Kristoffersen et al., 2021) have revealed exciting new scientific questions and potential drilling targets that can be exploited using MSP drilling capabilities. Along the remote northern coast of Greenland, ice conditions have rapidly become more amenable in recent years, facilitating logistically feasible work, as proven by the 2018 I/B *Polarstern* expedition that collected deep seismic data north of Peary Land (Damm, 2019). Based on the data availability, the key objectives of the NorthGreen MagellanPlus workshop were as follows:

1. to discuss the potential development of coordinated IODP MSP proposals in Northeast Greenland including both onshore and offshore operations, within short and long time frames;
2. to define specific Cenozoic drilling targets based on existing data;
3. to identify the data gaps in key research areas, e.g., along shelf to fjord transects;
4. to establish collaborations among the wide scientific community by integrating the results of past and forthcoming IODP expeditions around the Greenland margins and expanding this scientific network.

Table 1. Number of participants by country: 59 participants come from ECORD countries and 12 from non-ECORD countries (i.e., South Korea, New Zealand and the USA).

Country	No. participants
Denmark	21
Germany	13
US	8
Norway	5
UK	6
Sweden	6
Canada	4
South Korea	3
Ireland	1
Italy	1
New Zealand	1
Poland	1
The Netherlands	1
Total	71

4 Workshop structure and outcomes

4.1 Workshop attendance

The NorthGreen MagellanPlus workshop was held at GEUS in Copenhagen, Denmark, on 21–23 November 2022. The program included scientific and technical talks delivered by international keynote speakers, breakout sessions, and posters. Seventy-one participants represented a wide scientific community of marine scientists, paleoclimatologists, and terrestrial geologists and glaciologists (Fig. 2). The workshop included participants from 13 countries with 56 in-person and 15 online attendants (Table 1). Fifteen of the participants were early-career researchers. Thus, NorthGreen was a successful workshop that gathered an international, multidisciplinary group of scientists to discuss scientific objectives and hypotheses relevant for the Northeast Greenland margins and the adjoining ocean regions.

4.2 MSP proposals in Northeast Greenland

Scientific drilling of the Northeast Greenland margins allows research within all seven of the strategic objectives of the IODP 2050 Science Framework (Koppers and Coggon, 2020). In particular, the proposed objectives crucial for the Ground-Truthing Future Climate Change flagship initiative. Thus, the NorthGreen MagellanPlus workshop constituted the kickoff of a long-term (∼ 10 years) research strategy on the Northeast Greenland margins. During the workshop, key drilling areas were defined (Fig. 1). Highlighted topics were (i) the Greenland ice sheet extension during past interglacial periods; (ii) key Cenozoic intervals to provide paleo-constraints for future climate projections; (iii) climate and biosphere interactions; and (iv) oceanic gateways, specifically the Arctic–North Atlantic tectonic connections and

Figure 2. In-person participants of the NorthGreen MagellanPlus workshop at GEUS in November 2022 in Copenhagen, Denmark. Photo by GEUS.

their impact on global thermohaline circulation. The working teams and scientific objectives of three MSP proposals were outlined during the workshop.

4.2.1 Morris Jesup Rise: resurrecting an old pre-proposal

The Morris Jesup Rise (Area B in Fig. 1) extends ∼ 250 km into the central Arctic Ocean from the coast of northern Greenland. It is a conjugate feature to the Yermak Plateau with respect to the Gakkel Ridge (Fig. 3). These two physiographic features are believed to be of volcanic origin, formed at the triple junction between the Greenland, North American, and Eurasian plates. Estimates for the timing of volcanic emplacement vary widely, from the Late Cretaceous to Eocene–Oligocene times (Kristoffersen et al., 2021). The Morris Jesup Rise and Yermak Plateau were ultimately rifted apart by the propagation of seafloor spreading along the Gakkel Ridge between ∼ 33 and 25 Ma (Brozena et al., 2003; Gion et al., 2017), over 20 Myr after seafloor spreading began in the Eurasian Basin. The eventual opening of the Fram Strait had a profound impact on the oceanography of the Arctic and is marked in the ACEX record by a transition from poorly oxygenated to fully ventilated conditions (Jakobsson et al., 2007). New seismic data acquired from a floating ice station that crossed the Morris Jesup Rise in 2015 (Kristoffersen et al., 2016) have shown that a relatively thin drape (100 m) of Miocene/Pliocene to Present sediments overlay a peneplained unconformity that formed prior to the post-rifting subsidence of the Morris Jesup Rise (Kristoffersen et al., 2021). Constraining the timing and type of volcanic activity that formed the Morris Jesup Rise as well as its subsequent subsidence history would provide important new data for testing the current interpretation based on seafloor magnetic anomalies and for improving plate tectonic models on the development of the oceanic–continental region around northernmost Greenland.

The Atlantic water that enters the Arctic Ocean through the eastern Fram Strait and across the Barents Sea continues a cyclonic circulation along the continental slopes of the inner Arctic Ocean and reenters the Norwegian–Greenland Sea after passing the Morris Jesup Rise. Therefore, sedimentary archives from the Morris Jesup Rise would provide an integrated picture of water masses as they exit the Arctic Ocean and complement past (ODP Leg 151) and planned (IODP Expedition 403) expeditions to the eastern Fram Strait. Furthermore, the Morris Jesup Rise lies at the eastern edge of what has recently been termed the "Last Ice Area" (Newton et al., 2021), a region that hosts the oldest, thickest, and most persistent sea ice cover in the Arctic, making it an ideal target to recover long-term proxy-based insights into the persistence

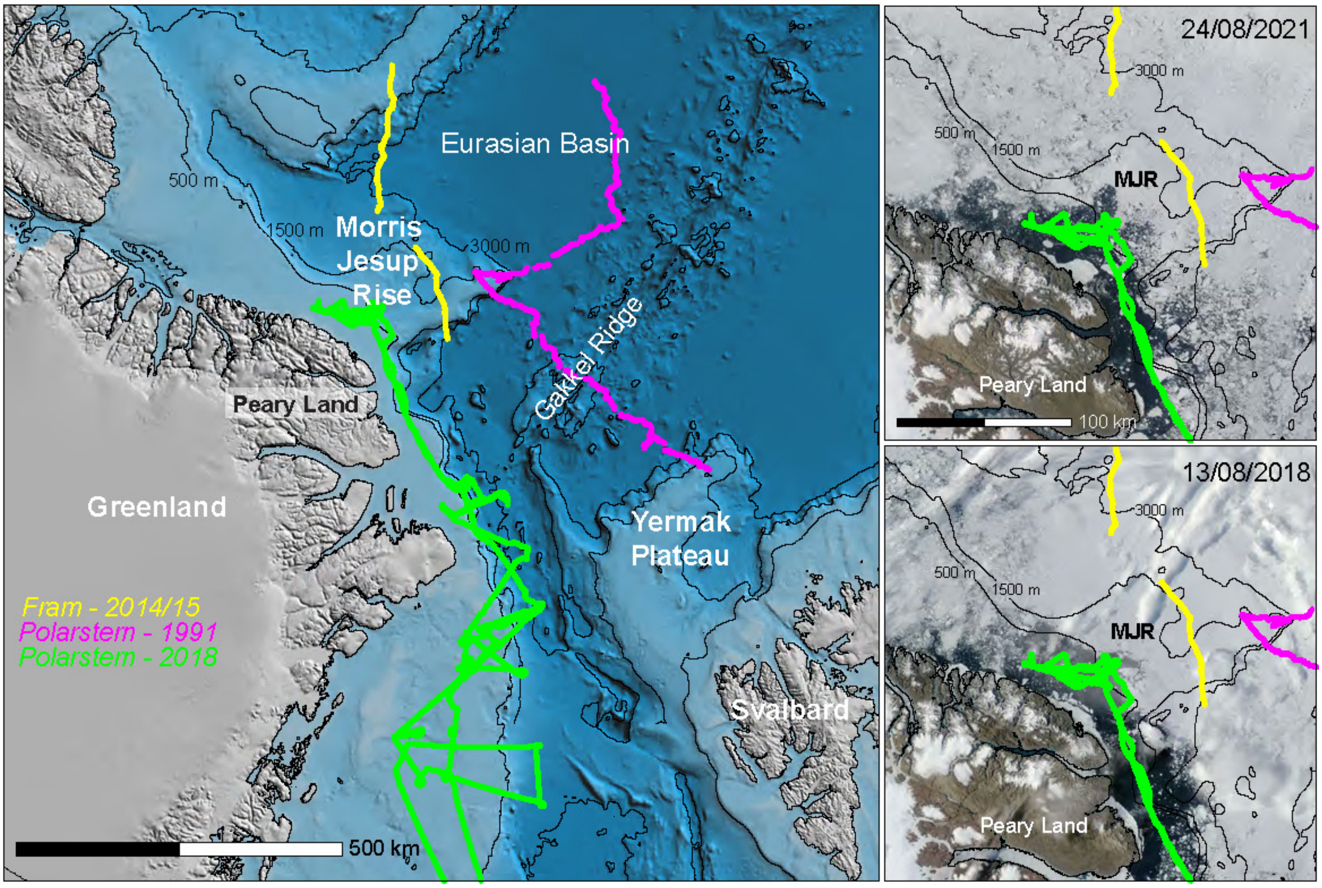


Figure 3. Geographic setting of Morris Jesup Rise (MJR) and Yermak Plateau flanking the Fram Strait. Seismic data crossing the MJR exist from three previous cruises (shown by the colored lines). Bathymetry is from the International Bathymetric Chart of the Arctic Ocean v.3.0 (Jakobsson et al., 2012). The right-hand panels show satellite images that illustrate examples of how the sea ice cover over MJR and the northern Greenland margin broke up in August 2018 (bottom) and August 2021 (top). Georeferenced satellite images were downloaded from https://worldview.earthdata.nasa.gov/ (last access: 24 July 2023).

of sea ice in the central Arctic Ocean as well as the provenance of ice-rafted material that is exiting the Arctic.

A previous pre-proposal for drilling on the Morris Jesup Rise was submitted in 2009 (756-Pre) and received favorable reviews by the Science Evaluation Panel of IODP. However, the lack of site survey data and concerns about proposing deep drilling sites in a region prone to harsh sea ice conditions stalled the development of a full proposal. The NorthGreen workshop served as a catalyst for the resurrection of the drilling initiative, largely in response to the increased feasibility of drilling due to the breakup of sea ice in the region, newly acquired seismic data illuminating exciting new scientific questions and drilling targets, and three upcoming expeditions to the area in 2024 and 2025 (by Sweden, Norway, and Germany) that can collect additional geophysical and coring data in support of a full drilling proposal (Areas D and E in Fig. 1). Thus, the two main scientific goals of drilling Morris Jesup Rise will be as follows:

1. refine the plate tectonic development of the oceanic–continental region around northernmost Greenland with a focus on the formation, rifting, and subsidence of the Morris Jesup Rise as well as the breakup between the Barents Sea and Northeast Greenland margin;

2. reconstruct the paleoceanographic evolution of the central Arctic Ocean, focusing on the inception and persistence of sea ice in the Last Ice Area, the fluxes and sources of water masses exiting the inner Arctic, and the Cenozoic dynamics of the northern Greenland and other circum-Arctic ice sheets.

4.2.2 Northeast Greenland continental shelf: IODP 1011-Pre

The Greenland margin has the widest continental shelf along Northeast Greenland (Fig. 4), where the shelf edge is located up to ∼ 300 km from the coastline and gives way to the

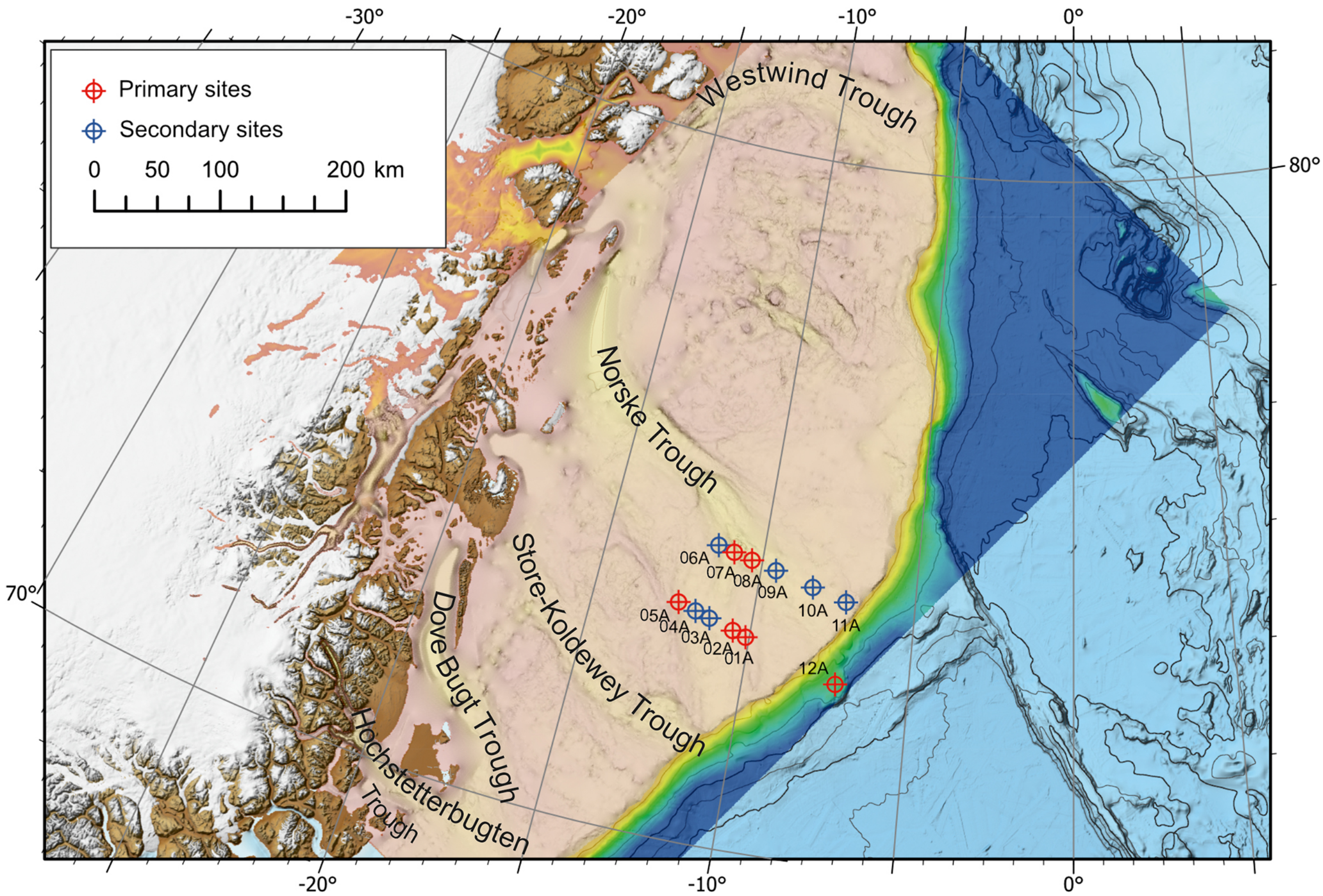


Figure 4. Proposed drilling sites in IODP proposal 1011-Pre "Northeast Greenland Glaciated Margin" on the continental shelf and slope of Northeast Greenland. The high-resolution bathymetric map of Arndt et al. (2015) is overlaid on the International Bathymetric Chart of the Arctic Ocean v.3.0 (Jakobsson et al., 2012).

abyssal plain of the northern North Atlantic Ocean through a steep slope characterized by lobed morphology (Arndt et al., 2015). Internally, the Northeast Greenland continental shelf consists of major Paleozoic–Mesozoic basins formed during multiple phases of rifting that preceded the North Atlantic seafloor spreading around 56–54 Ma (Hamann et al., 2005; Stoker et al., 2016; Abdelmalak et al., 2023). Early volcanic activity and the occurrence of salt diapirs and hydrocarbons within the shelf basins have completed the margin structure (Hamann et al., 2005; Fyhn and Hopper, 2024). However, the Cenozoic history of Northeast Greenland has been marked by repeated erosion by ice streams emanating from the major fjords which subsequently coalesced offshore to form overdeepened cross-shelf troughs (Fig. 4).

The first emergence of a stable Greenland-wide ice sheet is usually related to the initial cooling phase of the Northern Hemisphere glaciation during the Quaternary (e.g., Bailey et al., 2013). Nevertheless, ephemeral ice sheets have been tracked back to the late Eocene (e.g., Maslin et al., 1998; Darby, 2014), and identified ice-rafted debris from ODP Sites 913 and 918 has been interpreted as originating from a permanent ice sheet covering east Greenland during the late Eocene and middle Miocene (e.g., Tripati et al., 2008; Thiede et al., 2010). However, both ODP sites are located on the abyssal plain away from the present-day Greenland coastline and, thus, do not record initial ice sheet inception. Determining the timing of the initial cross-shelf glaciation on Northeast Greenland would constrain the environmental conditions of the transition from land-based to marine-based ice sheets in the Northern Hemisphere.

The Northeast Greenland ice stream drains about 20 % of the Greenland ice sheet (Zwally et al., 2012). During previous glacial periods, carving offshore troughs, such as the Norske Trough (Fig. 4), led to the deposition of trough-mouth fans at the shelf edge (Fahnestock et al., 2001; Arndt et al., 2015). However, during warm interglacials, the warm water from the Return Atlantic Water reaches the inner continental shelf in Northeast Greenland, flowing through the shelf troughs (Straneo et al., 2017; Schaffer et al., 2020). Distinct climatic forcings have influenced the dynamics of the Greenland ice sheet, changing the role of the continental shelf troughs from ice-flow channels to warm-water conducts. Knowledge of the dynamics of the Greenland ice sheet during consecutive glacial–interglacial cycles is essential to understand its response to warm climates.

Following the NorthGreen workshop, IODP proposal 1011-Pre was submitted in April 2023 under the title "Northeast Greenland Glaciated Margin". Due to positive feedback from the IODP Science Evaluation Panel, a full proposal is currently under development. The proposal focuses on the Greenland ice sheet as a tipping point within the Earth's climate system. Understanding the long-term stability of the Greenland ice sheet is critical for anticipating future climate and sea level scenarios, as the continental margin of Northeast Greenland constitutes a missing piece in this context (Area A in Fig. 1). The proposed drilling on the prograded shelf margin targets trough-mouth fans and buried contourite deposits as archives of the past evolution of the Greenland ice sheet. The highlighted objectives of the proposal are as follows: (1) to illuminate the timing and environmental conditions at the onset of glacial expansion, (2) to understand the dynamics of the Greenland ice sheet during abrupt changes in atmospheric and oceanographic conditions, and (3) to investigate the effects of regional tectonic and oceanographic changes on the polar cryosphere evolution. The drilling strategy consists of six primary sites complemented by six alternate sites along transects crossing the continental shelf and slope on the Norske Trough (Fig. 4). Discussions on further possibilities for onshore scientific drilling have been initiated. Several onshore projects lead by workshop participants have been highlighted as an initial step towards land-to-sea connections in Northeast Greenland (e.g., GreenDrill, 2023), with both a short-term and long-term perspective.

4.2.3 Denmark Strait gateway: DenGate proposal outline

DenGate is a recently formed international collaborative venture that focuses on paleoceanography and tectonic evolution of the Denmark Strait oceanic gateway (Fig. 5). The Denmark Strait, between Greenland and Iceland, and the Faroe–Iceland Ridge/Faroe–Shetland Basin, between Iceland and Scotland, are gateways within the Greenland–Scotland Ridge. The Greenland–Scotland Ridge is a shallow sill of thick oceanic crust that formed above the Icelandic mantle plume and constitutes an important barrier within the AMOC system, as it separates the main Atlantic Ocean from the Nordic Seas (and hence the Arctic Ocean). The Nordic Seas (or northern North Atlantic Ocean) are one of the two main global production sites of cold, deep ocean water. At present, the combined southward deepwater flow through the Denmark Strait and Faroe–Iceland Ridge gateways directly contributes about one-third of AMOC, and it indirectly influences the remainder (Hansen et al., 2004). The AMOC has fluctuated in strength considerably over timescales from decades to millions of years, and these changes correlate with changes in Northern Hemisphere climate (Rahmstorf, 2002). Community effort has been requested to resolve which components and pathways of the AMOC have altered, how, and why (Ceasar et al., 2021).

The age of the first opening of Denmark Strait is unclear. The Greenland–Scotland Ridge has been affected by a complicated series of oceanic spreading axis relocations ever since the breakup of Greenland and northwestern Europe in the earliest Eocene (Hardarson et al., 1997). It is not known whether the oceanic crust beneath the Denmark Strait was formed by a northward projection of the Reykjanes Ridge (the current plate boundary to the south of Iceland) or a southward projection of the Kolbeinsey Ridge (the current plate boundary to the north of Iceland). Thus, the age of the oceanic basement beneath the Denmark Strait is uncertain; consequently, there are large uncertainties in oceanic plate subsidence models with respect to its opening. Notwithstanding these uncertainties, some models predict that the Denmark Strait first opened during the Miocene, ~ 20 to 10 Ma (Poore et al., 2006; Straume et al., 2020). Thus, there is considerable uncertainty regarding the role of the Denmark Strait in the EGC initiation. After its initial opening, subsidence of the Denmark Strait gateway was probably influenced by fluctuations in activity of the Icelandic mantle plume. Fluctuations in the accumulation of sediment drifts to the south of Iceland have been interpreted to mean that plume-driven vertical motions of the Denmark Strait and Faroe–Iceland Ridge gateways have influenced the AMOC (Parnell-Turner et al., 2015). This hypothesis was a main basis for the recent IODP Expedition 395. However, higher-frequency fluctuations in AMOC, including a dramatic weakening over the past century (Ceasar et al., 2021), cannot have been driven by tectonics and rather point to a complex relationship between AMOC, climate, and tectonics.

Direct measurements of deepwater flow through the Denmark Strait, termed Denmark Strait Overflow Water (DSOW), at high temporal resolution are required to resolve these questions. Therefore, the main aims of the DenGate proposal are (1) to clarify the age of the first opening of the Denmark Strait by determining the ages of the oceanic basement and the oldest sediments and (2) to obtain a continuous record of the overflow water fluctuations across the Denmark Strait from contourite drift deposits near the gateway.

Multiple IODP, ODP, and DSDP sites in sediment drifts within the Norwegian Sea (north of the Greenland–Scotland Ridge) and the Rockall Trough and Iceland Basin (south of the Greenland–Scotland Ridge) are available to study the Paleogene–Holocene history of oceanic flow across the Faroe–Iceland Ridge (Fig. 5). This effort continued in 2023 with drilling of the Björn and Gardar drifts in the Iceland Basin by IODP Expedition 395, and seismic site surveying of sediment drifts in the Norwegian Sea is currently scheduled to support future drilling campaigns (Gabi Uenzelmann-Neben, personal communication, 2023). However, none of this activity can directly reconstruct DSOW. The complicating factor is that current branches diverge from the EGC

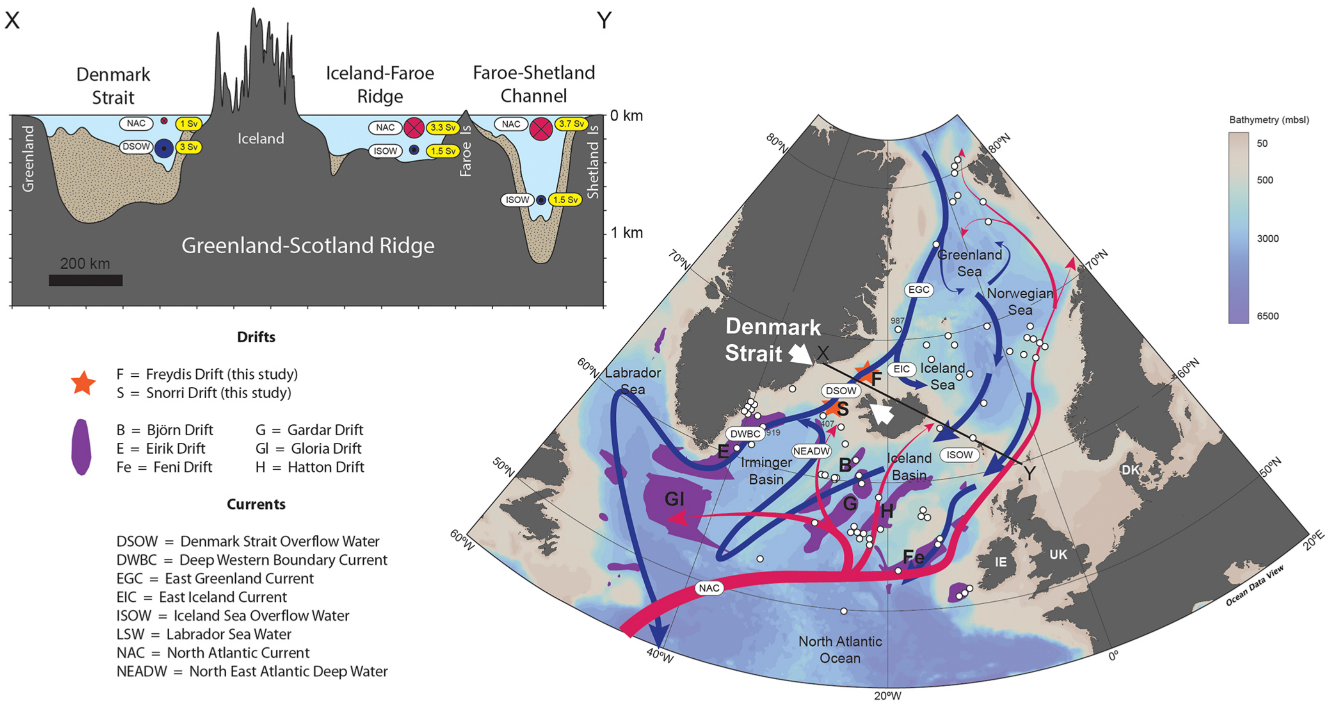


Figure 5. Oceanographic context for the DenGate drilling proposal. Red and blue arrows indicate respective warm surface and cold deep ocean currents that comprise the northern hub of the Atlantic Meridional Overturning Circulation. Note that much of the sediment illustrated beneath the Denmark Strait section is derived from the continental shelf; the areal extents and thicknesses of the Snorri and Freydis drifts (orange stars) are unclear and require further seismic site survey. White circles show IODP, ODP, and DSDP sites. The data used to create the figure were sourced from the Ocean Data View software (Schlitzer, Reiner, Ocean Data View, http://odv.awi.de, 2023, last access: December 2023).

close to the north of the Denmark Strait and converge with the EGC close to the south of the Denmark Strait (Fig. 5). Therefore, only by undertaking drilling close to the Denmark Strait itself can we directly reconstruct variations in DSOW and, thus, clarify the relative roles of the Denmark Strait and Faroe–Iceland Ridge gateways in controlling AMOC. The Snorri Drift is a contourite drift accumulating on the southern flank of the Denmark Strait ridge as well as beneath the Denmark Strait itself. Shallow cores in the Snorri Drift have been used to reconstruct the past 240 kyr of fluctuations in DSOW, but the drift has never been cored to basement (Andrews et al., 2021). There is very little information available on the sediments immediately north of the Denmark Strait, in the Blosseville Basin between Greenland and the Kolbeinsey Ridge. Therefore, the DenGate working group began by assembling and interpreting the very sparse legacy seismic data available from this region. A promising sediment drift target, which they name the Freydis Drift (Fig. 5), has been identified and appears to be thicker than the Snorri Drift (Jones et al., 2024). The next steps, which we aim to achieve during 2024, are to propose a seismic site survey of the Snorri and Freydis drifts and, simultaneously, to submit an outline proposal for drilling to the European Consortium for Ocean Research Drilling (ECORD).

5 Concluding remarks and future work

The Greenland ice sheet is a tipping element within the Earth's climate system; thus, understanding its long-term stability is critical for anticipating future climate and sea level scenarios. Whereas scientific drilling has been implemented on the West Greenland margin and deep areas of the northern North Atlantic Ocean, Northeast Greenland constitutes a data gap preventing accurate reconstructions of the Cenozoic climate–tectonic evolution and hampering our ability to estimate ice sheet instability and associated sea level rise under the current trend of climate change. During the NorthGreen MagellanPlus workshop, knowledge gaps were highlighted, and scientific targets were addressed, with focus on developing a long-term research strategy for illuminating ice–ocean–tectonic interactions in Northeast Greenland. This includes further scientific drilling through IODP mission-specific platforms; currently, three drilling proposals are being developed with the aim of addressing pressing questions within the Ground-Truthing Future Climate Change flagship initiative.

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

Workshop participants list. The following researchers participated in the NorthGreen MagellanPlus workshop: Allison Cluett (Buffalo University, New York, USA), Anne de Vernal (Université du Québec à Montréal, Montreal, Canada), Antonia Ruppel (BGR, Hanover, Germany), Bernard Coakley (University of Alaska, Anchorage, USA), Camilla Snowman Andresen (GEUS, Copenhagen, Denmark), Catalina Gebhardt (AWI, Bremerhaven, Germany), Christian Schiffer (Uppsala University, Uppsala, Sweden), Christian Tegner (Aarhus University, Aarhus, Denmark), Christoph Böttner (Kiel University, Kiel, Germany), Colm O'Cofaigh (Durham University, Durham, UK), Cornelia Spiegel-Behnke (University of Bremen, Bremen, Germany), David McInroy (BGS, Edinburgh, UK), Dave Roberts (Durham University, Durham, UK), Dieter Franke (BGR, Hanover, Germany), Drew Christ (University of Vermont, Burlington, USA), Eivind O. Straume (University of Texas at Austin, Austin, Texas, USA), Elizabeth Thomas (Buffalo University, New York, USA), Emilie R. Bennedsen (University of Copenhagen, Copenhagen Denmark), Gabriele Uenzelmann-Neben (AWI, Bremerhaven, Germany), Grace Shephard (University of Oslo, Oslo, Norway), Gregers Dam (GEUS, Copenhagen, Denmark), Gunnar Sand (SINTEF, Oslo, Norway), Henk Brinkhuis (Utrecht University, Utrecht, the Netherlands), James Barnett (Stockholm University, Stockholm, Sweden), Jason Briner (Buffalo University, New York, USA), Jeremy Lloyd (Durham University, Durham, UK), John Hopper (GEUS, Copenhagen, Denmark), Joseph Stoner (Oregon State University, Corvallis, USA), Jung-Hyun Kim (KOPRI, Incheon, South Korea), Karsten Gohl (AWI, Bremerhaven, Germany), Kasia Sliwinska (GEUS, Copenhagen, Denmark), Katrin Meier (University of Bremen, Bremen, Germany), Katrine Juul Andresen (Aarhus University, Aarhus, Denmark), Kelly Hogan (BAS, Cambridge, UK), Kwangchul Jang (KOPRI, Incheon, South Korea), Lara F. Pérez (GEUS, Aarhus, Denmark), Lis Allaart (GEUS, Aarhus, Denmark), Lutz Reinhardt (BGR, Hanover, Germany), Maciej Jez (Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland), Madeleine Larissa Vickers (University of Oslo, Oslo, Norway), Marit-Solveig Seidenkrantz (Aarhus University, Aarhus, Denmark), Martin Jakobsson (Stockholm University, Stockholm, Sweden), Mary-Lynn Dickson (RN Canada, Halifax, Canada), Matt O'Regan (Stockholm University, Stockholm, Sweden), Michael Bryld Wessel Fyhn (GEUS, Copenhagen, Denmark), Monica Winsborrow (UiT – The Arctic University of Norway, Tromsø Norway), Morten Bjerager (GEUS, Copenhagen, Denmark), Naima El bani Altuna (UiT – The Arctic University of Norway, Tromsø Norway), Niels Jákup Korsgaard (GEUS, Copenhagen, Denmark), Ole Bennike (GEUS, Copenhagen, Denmark), Paul Knutz (GEUS, Copenhagen, Denmark), Peter Klitzke (BGR, Hanover, Germany), Rebecca Pickering (Lund University, Lund, Sweden), Renata Giulia Lucchi (OGS, Trieste, Italy), Richard Levy (GNS Science, Wellington, New Zealand), Sarah Benetti (Ulster University, Ulster, Northern Ireland), Sean Gulick (Texas A&M, College Station, USA), Seung-Il Nam (KOPRI, Incheon, South Korea), Sofia Ribeiro (GEUS, Copenhagen, Denmark), Stephen Grasby (Geological Survey of Canada, Alberta, Canada), Stephen Jones (University of Birmingham, Birmingham, UK), Sverre Planke (VBPR, Oslo, Norway), Thomas Funk (GEUS, Copenhagen, Denmark), Thorsten Nagel (Aarhus University, Aarhus, Denmark), Tove Nielsen (GEUS, Copenhagen, Denmark), Trine Dahl-Jensen (GEUS, Copenhagen, Denmark), Vivi Kathrine Pedersen (Aarhus University, Aarhus, Denmark), Wei-Li Hong (Stockholm University, Stockholm, Sweden), and Wolfram Geissler (AWI, Bremerhaven, Germany).

Author contributions. LFP wrote the core portion of the manuscript and was the main organizer of the NorthGreen MagellanPlus workshop. LFP led the 1011-Pre proposal. PCK, JRH, MSS, and MO'R provided input on the manuscript text and were co-organizers of the workshop. MSS was the ECORD-appointed watchdog during workshop organization. JRH made the figure base maps. As proposal leader, MO'R wrote the core portion of Sect. 4.2.1. As leader of DenGate initiative, SJ provided input on the manuscript text and wrote the core portion of Sect. 4.2.3.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. Funding for the organization of the NorthGreen MagellanPlus workshop was provided by the MagellanPlus Workshop Series Programme of ECORD and by the Carlsberg Foundation. We acknowledge the participation and enthusiasm of all of the workshop participants. We acknowledge the editor Nadine Hallmann and the reviews by Wilfried Jokat and an anonymous reviewer which greatly improved the initial version of this work.

Financial support. This research has been supported by the Carlsbergfondet (grant no. CF22-0160) and the MagellanPlus Workshop Series Programme of ECORD.

Review statement. This paper was edited by Nadine Hallmann and reviewed by Wilfried Jokat and one anonymous referee.

References

Abdelmalak, M. M., Gac, S., Faleide, J. I., Shephard, G. E., Tsikalas, F., Polteau, S., Zastrozhnov, D., and Torsvik, T. H.: Quantification and Restoration of the Pre-Drift Extension Across the NE Atlantic Conjugate Margins During the Mid-Permian-Early Cenozoic Multi-Rifting Phases, Tectonics, 42, e2022TC007386, https://doi.org/10.1029/2022tc007386, 2023.

Andrews, J. T., McCave, I. N., and Syvitski, J.: A ∼240 ka record of Ice Sheet and Ocean interactions on the Snorri Drift, SW of Iceland, Global Planet. Change, 201, 103498, https://doi.org/10.1016/j.gloplacha.2021.103498, 2021.

Arndt, J. E., Jokat, W., Dorschel, B., Myklebust, R., Dowdeswell, J. A., and Evans, J.: A new bathymetry of the Northeast Greenland continental shelf: Constraints on glacial and other processes, Geochem. Geophy. Geosy., 16, 3733–3753, https://doi.org/10.1002/2015GC005931, 2015.

Bailey, I., Hole, G. M., Foster, G. L., Wilson, P. A., Storey, C. D., Trueman, C. N., and Raymo, M. E.: An alternative suggestion for the Pliocene onset of major northern hemisphere glaciation based on the geochemical provenance of North Atlantic Ocean ice-rafted debris, Quaternary Sci. Rev., 75, 181–194, https://doi.org/10.1016/j.quascirev.2013.06.004, 2013.

Bennike, O., Abrahamsen, N., Bak, M., Israelson, C., Konradi, P., Matthiessen, J., and Witkowski, A.: A multiproxy study of Pliocene sediments from Île de France, North-East Greenland, Palaeogeogr. Palaeocl., 186, 1–23, https://doi.org/10.1016/S0031-0182(02)00439-X, 2002.

Bennike, O. L. E., Knudsen, K. L., Abrahamsen, N., BÖCher, J., Cremer, H., and Wagner, B.: Early Pleistocene sediments on Store Koldewey, northeast Greenland, Boreas, 39, 603–619, https://doi.org/10.1111/j.1502-3885.2010.00147.x, 2010.

Berger, D. and Jokat, W.: A seismic study along the East Greenland margin from 72° N to 77° N, Geophys. J. Int., 174, 733–748, https://doi.org/10.1111/j.1365-246X.2008.03794.x, 2008.

Berger, D. and Jokat, W.: Sediment deposition in the northern basins of the North Atlantic and characteristic variations in shelf sedimentation along the East Greenland Margin, Mar. Petrol. Geol., 26, 1321–1337, https://doi.org/10.1016/j.marpetgeo.2009.04.005, 2009.

Bierman, P. R., Shakun, J. D., Corbett, L. B., Zimmerman, S. R., and Rood, D. H.: A persistent and dynamic East Greenland ice sheet over the past 7.5 million years, Nature, 540, 256–260, https://doi.org/10.1038/nature20147, 2016.

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K., and Bamber, J. L.: Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean, Nat. Geosci., 9, 523–527, https://doi.org/10.1038/ngeo2740, 2016.

Brozena, J. M., Childers, V. A., Lawver, L. A., Gahagan, L. M., Forsberg, R., Faleide, J. I., and Eldholm, O.: New aerogeophysical study of the Eurasia Basin and Lomonosov Ridge: Implications for basin development, Geology, 31, 825–828, https://doi.org/10.1130/G19528.1, 2003.

Budéus, G. and Schneider, W.: On the hydrography of the Northeast Water Polynya, J. Geophys. Res., 100, 4287–4299, https://doi.org/10.1029/94JC02024, 1995.

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., and Rahmstorf, S.: Current Atlantic Meridional Overturning Circulation weakest in last millennium, Nat. Geosci., 14, 118–120, https://doi.org/10.1038/s41561-021-00699-z, 2021.

Christ, A. J., Rittenour, T. M., Bierman, P. R., Keisling, B. A., Knutz, P. C., Thomsen, T. B., Keulen, N., Fosdick, J. C., Hemming, S. R., Tison, J.-L., Blard, P.-H., Steffensen, J. P., Caffee, M. W., Corbett, L. B., Dahl-Jensen, D., Dethier, D. P., Hidy, A. J., Perdrial, N., Peteet, D. M., Steig, E. J., and Thomas, E. K.: Deglaciation of northwestern Greenland during Marine Isotope Stage 11, Science, 381, 330–335, https://doi.org/10.1126/science.ade4248, 2023.

Christiansen, F. G.: Greenland petroleum exploration history: Rise and fall, learnings, and future perspectives, Resour. Policy, 74, 102425, https://doi.org/10.1016/j.resourpol.2021.102425, 2021.

Clotten, C., Stein, R., Fahl, K., Schreck, M., Risebrobakken, B., and De Schepper, S.: On the causes of Arctic sea ice in the warm Early Pliocene, Sci. Rep., 9, 989, https://doi.org/10.1038/s41598-018-37047-y, 2019.

Damm, E. A.: The Expedition PS115/1 of the Research Vessel *POLARSTERN* to the Greenland Sea and Wandel Sea in 2018, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, https://doi.org/10.2312/BzPM_0727_2019, 2019.

Darby, D. A.: Ephemeral formation of perennial sea ice in the Arctic Ocean during the middle Eocene, Nat. Geosci., 7, 210–213, https://doi.org/10.1038/ngeo2068, 2014.

Davies, S., Stow, D., and Nicholson, U.: Late glacial to Holocene sedimentary facies of the Eirik Drift, southern Greenland margin: Spatial and temporal variability and paleoceanographic implications, Mar. Geol., 440, 106568, https://doi.org/10.1016/j.margeo.2021.106568, 2021.

De Schepper, S., Schreck, M., Beck, K. M., Matthiessen, J., Fahl, K., and Mangerud, G.: Early Pliocene onset of modern Nordic Seas circulation related to ocean gateway changes, Nat. Commun., 6, 8659, https://doi.org/10.1038/ncomms9659, 2015.

Døssing, A., Japsen, P., Watts, A. B., Nielsen, T., Jokat, W., Thybo, H., and Dahl-Jensen, T.: Miocene uplift of the NE Greenland margin linked to plate tectonics: Seismic evidence from the Greenland Fracture Zone, NE Atlantic, Tectonics, 35, 257–282, https://doi.org/10.1002/2015TC004079, 2016.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S., and Raymo, M. E.: Sea-level rise due to polar ice-sheet mass loss during past warm periods, Science, 349, aaa4019, https://doi.org/10.1126/science.aaa4019, 2015.

Ehlers, B.-M. and Jokat, W.: Paleo-bathymetry of the northern North Atlantic and consequences for the opening of the Fram Strait, Mar. Geophys. Res., 34, 25–43, https://doi.org/10.1007/s11001-013-9165-9, 2013.

Engen, Ø., Faleide, J. I., and Dyreng, T. K.: Opening of the Fram Strait gateway: A review of plate tectonic constraints, Tectonophysics, 450, 51–69, https://doi.org/10.1016/j.tecto.2008.01.002, 2008.

Escutia, C., DeConto, R., Dunbar, R., De Santis, L., Shevenell, A., and Nash, T.: Keeping an Eye on Antarctic Ice Sheet Stability, Oceanography, 32, 32–46, https://doi.org/10.5670/oceanog.2019.117, 2019.

Fahnestock, M., Abdalati, W., Joughin, I., Brozena, J., and Gogineni, P.: High Geothermal Heat Flow, Basal Melt, and the Origin of Rapid Ice Flow in Central Greenland, Science, 294, 2338–2342, https://doi.org/10.1126/science.1065370, 2001.

Fyhn, M. B. W. and Hopper, J. R.: NE Greenland Composite Tectono-Sedimentary Element, northern Greenland Sea and Fram Strait, Geological Society, London, Memoirs, 57, M57-2017-2012, https://doi.org/10.1144/M57-2017-12, 2024.

Gaina, C., Nasuti, A., Kimbell, G. S., and Blischke, A.: Break-up and seafloor spreading domains in the NE Atlantic, in: The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution, edited by: Pinvidic, G., Hopper, J. R., Stoker, M. S., Gaina, C., Doornenbal, J. C., Funck, T., and Árting, U. E., Geological Society of London, 393–417, https://doi.org/10.1144/sp447.12, 2017.

Gion, A. M., Williams, S. E., and Müller, R. D.: A reconstruction of the Eurekan Orogeny incorporating deformation constraints, Tectonics, 36, 304–320, https://doi.org/10.1002/2015tc004094, 2017.

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., and Edwards, T. L.: Global environmental consequences of twenty-first-century ice-sheet melt, Nature, 566, 65–72, https://doi.org/10.1038/s41586-019-0889-9, 2019.

GreenDrill: https://greendrill-cosmo.ldeo.columbia.edu/, last access: June 2023.

Hamann, N. E., Whittaker, R. C., and Stemmerik, L.: Geological development of the Northeast Greenland shelf, in: Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference, edited by: Doré, A. G. and Vining, B. A., Petroleum Geology Conferences Ltd., Geological Society, London, 887–902, 2005.

Hansen, B., Østerhus, S., Quadfasel, D., and Turrell, B.: Already the Day After Tomorrow?, Science, 305, 953–954, https://doi.org/10.1126/science.1100085, 2004.

Hardarson, B. S., Fitton, J. G., Ellam, R. M., and Pringle, M. S.: Rift relocation – A geochemical and geochronological investigation of a palaeo-rift in northwest Iceland, Earth Planet. Sc. Lett., 153, 181–196, https://doi.org/10.1016/S0012-821X(97)00145-3, 1997.

Heirman, K., Nielsen, T., and Kuijpers, A.: Impact of Tectonic, Glacial and Contour Current Processes on the Late Cenozoic Sedimentary Development of the Southeast Greenland Margin, Geosciences, 9, 157, https://doi.org/10.3390/geosciences9040157, 2019.

Hofer, S., Lang, C., Amory, C., Kittel, C., Delhasse, A., Tedstone, A., and Fettweis, X.: Greater Greenland ice sheet contribution to global sea level rise in CMIP6, Nat. Commun., 11, 6289, https://doi.org/10.1038/s41467-020-20011-8, 2020.

IPCC: Summary for Policymakers, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H. O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegri´a, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., in press, 2019.

Jakobsson, M., Backman, J., Rudels, B., Nycander, J., Frank, M., Mayer, L., Jokat, W., Sangiorgi, F., O'Regan, M., Brinkhuis, H., King, J., and Moran, K.: The early Miocene onset of a ventilated circulation regime in the Arctic Ocean, Nature, 447, 986–990, https://doi.org/10.1038/nature05924, 2007.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G., and Weatherall, P.: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, Geophys. Res. Lett., 39, L12609, https://doi.org/10.1029/2012GL052219, 2012.

Jansen, E., Raymo, M. E., and Blum, P.: Proceedings, initial reports, Ocean Drilling Program, Leg 162, North Atlantic-Arctic gateways II, ODP, Texas A and M University, College Station, ISSN 0884-5883, 1996.

Jokat, W., Lehmann, P., Damaske, D., and Bradley Nelson, J.: Magnetic signature of North-East Greenland, the Morris Jesup Rise, the Yermak Plateau, the central Fram Strait: Constraints for the rift/drift history between Greenland and Svalbard since the Eocene, Tectonophysics, 12, 98–109, https://doi.org/10.1016/j.tecto.2015.12.002, 2015.

Jones, S. M., Hopper, J. R., Pérez, L. F., Hall, J. R., Uenzelmann-Neben, G., and Fyhn, M.: Potential for scientific drilling of sediment drifts adjacent to Denmark Strait oceanic gateway, Geological Society of London Special Publication, in review, 2024.

Knutz, P. C., Jennings, A., Childress, L. B., and Scientists, T. E.: Expedition 400 Preliminary Report: NW Greenland Glaciated Margin, International Ocean Discovery Program Preliminary Report, International Ocean Discovery Program, https://doi.org/10.14379/iodp.pr.400.2024, 2024.

Koppers, A. and Coggon, R.: Exploring Earth by scientific ocean drilling, 2050 Science Framework, 124, 2020.

Kristoffersen, Y., Tholfsen, A., Hall, J. K., and Stein, R.: Scientists spend Arctic winter adrift on sea ice, Eos, 97, 1/10, https://doi.org/10.1029/2016EO060711, 2016.

Kristoffersen, Y., Hall, J. K., and Nilsen, E. H.: Morris Jesup Spur and Rise north of Greenland – exploring present seabed features, the history of sediment deposition, volcanism and tectonic deformation at a Late Cretaceous/early Cenozoic triple junction in the Arctic Ocean, Norw. J. Geol., 101, 202104, https://doi.org/10.17850/njg101-1-4, 2021.

Larsen, H. C., Saunders, A. D., Clift, P. D., Ali, J., Begét, J., Cambray, H., Demant, A., Fitton, G., Fram, M. S., Fukuma, K., Gieskes, J., Holmes, M. A., Hunt, J., Lacasse, C., Larsen, L. M., Lykke-Anderson, H., Meltser, A., Morrison, M. L., Nemoto, N., Okay, N., Saito, S., Sinton, C., Spezzaferri, S., Stax, R., Vallier, T. L., Vandamme, D., Wei, W., and Werner, R.: Seven million years of glaciation in Greenland, Science, 264, 952–955, 1994.

Larsen, N. K., Levy, L. B., Carlson, A. E., Buizert, C., Olsen, J., Strunk, A., Bjørk, A. A., and Skov, D. S.: Instability of the Northeast Greenland Ice Stream over the last 45,000 years, Nat. Commun., 9, 1872–1872, https://doi.org/10.1038/s41467-018-04312-7, 2018.

Lucchi, R. G., St. John, K., and Ronge, T. A.: Expedition 403 Scientific Prospectus: Eastern Fram Strait Paleo-Archive (FRAME), International Ocean Discovery Program Scientific Prospectus, IODP, https://doi.org/10.14379/iodp.sp.403.2023, 2023.

Maslin, M. A., Li, X. S., Loutre, M. F., and Berger, A.: The contribution of orbital forcing to the progressive intensification of Northern Hemisphere Glaciation, Quaternary Sci. Rev., 17, 411–426, https://doi.org/10.1016/S0277-3791(97)00047-4, 1998.

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B. P. Y., O'Cofaigh, C., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglersen, K. B.: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation, Geophys. Res. Lett., 44, 11051–11061, https://doi.org/10.1002/2017gl074954, 2017.

Newton, R., Pfirman, S., Tremblay, L. B., and DeRepentigny, P.: Defining the "Ice Shed" of the Arctic Ocean's Last Ice Area and Its Future Evolution, Earths Future, 9, e2021EF001988, https://doi.org/10.1029/2021ef001988, 2021.

Notz, D. and SIMIP Community: Arctic Sea Ice in CMIP6, Geophys. Res. Lett., 47, e2019GL086749, https://doi.org/10.1029/2019gl086749, 2020.

Parnell-Turner, R., White, N. J., McCave, I. N., Henstock, T. J., Murton, B., and Jones, S. M.: Architecture of North Atlantic contourite drifts modified by transient circulation of the Icelandic mantle plume, Geochem. Geophy. Geosy., 16, 3414–3435, https://doi.org/10.1002/2015GC005947, 2015.

Pérez, L. F., Nielsen, T., Knutz, P. C., Kuijpers, A., and Damm, V.: Large-scale evolution of the central-east Greenland margin: New insights to the North Atlantic glaciation history, Global Planet. Change, 163, 141–157, https://doi.org/10.1016/j.gloplacha.2017.12.010, 2018.

Poirier, A. and Hillaire-Marcel, C.: Improved Os-isotope stratigraphy of the Arctic Ocean, Geophys. Res. Lett., 38, L14607, https://doi.org/10.1029/2011gl047953, 2011.

Poore, H. R., Samworth, R., White, N. J., Jones, S. M., and McCave, I. N.: Neogene overflow of Northern Component Water at the Greenland-Scotland Ridge, Geochem. Geophy. Geosy., 7, Q06010, https://doi.org/10.1029/2005gc001085, 2006.

Rahmstorf, S.: Ocean circulation and climate during the past 120,000 years, Nature, 419, 207–214, https://doi.org/10.1038/nature01090, 2002.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J. T. M.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38, L05503, https://doi.org/10.1029/2011gl046583, 2011.

Rudels, B.: Arctic Ocean Circulation, in: Encyclopedia of Ocean Sciences, Elsevier Ltd, 211–225, https://doi.org/10.1016/B978-012374473-9.00601-9, 2009.

Schaefer, J. M., Finkel, R. C., Balco, G., Alley, R. B., Caffee, M. W., Briner, J. P., Young, N. E., Gow, A. J., and Schwartz, R.: Greenland was nearly ice-free for extended periods during the Pleistocene, Nature, 540, 252–255, https://doi.org/10.1038/nature20146, 2016.

Schaffer, J., Kanzow, T., von Appen, W.-J., von Albedyll, L., Arndt, J. E., and Roberts, D. H.: Bathymetry constrains ocean heat supply to Greenland's largest glacier tongue, Nat. Geosci., 13, 227–231, https://doi.org/10.1038/s41561-019-0529-x, 2020.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V. R., Bjørk, A. A., Blazquez, A., Bonin, J., Colgan, W., Csatho, B., Cullather, R., Engdahl, M. E., Felikson, D., Fettweis, X., Forsberg, R., Hogg, A. E., Gallee, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K. K., Konrad, H., Langen, P. L., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mottram, R., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noël, B., Otosaka, I., Pattle, M. E., Peltier, W. R., Pie, N., Rietbroek, R., Rott, H., Sandberg Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K.-W., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W. J., van der Wal, W., van Wessem, M., Vishwakarma, B. D., Wiese, D., Wilton, D., Wagner, T., Wouters, B., Wuite, J., and The IMBIE Team: Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 579, 233–239, https://doi.org/10.1038/s41586-019-1855-2, 2020.

Smith, A. G. and Pickering, K. T.: Oceanic gateways as a critical factor to initiate icehouse Earth, J. Geol. Soc., 160, 337–340, https://doi.org/10.1144/0016-764902-115, 2003.

Solheim, A., Faleide, J. I., Andersen, E. S., Elverhøi, A., Forsberg, C. F., Vanneste, K., Uenzelmann-Neben, G., and Channell, J. E. T.: Late cenozoic seismic stratigraphy and glacial geological development of the East Greenland and Svalbard-Barents sea continental margins, Quaternary Sci. Rev., 17, 155–184, https://doi.org/10.1016/S0277-3791(97)00068-1, 1998.

St. John, K. E. K. and Krissek, L. A.: The late Miocene to Pleistocene ice-rafting history of Southeast Greenland, Boreas, 31, 28–35, https://doi.org/10.1111/j.1502-3885.2002.tb01053.x, 2002.

Stoker, M. S., Stewart, M. A., Shannon, P. M., Bjerager, M., Nielsen, T., Blischke, A., Hjelstuen, B. O., Gaina, C., McDermott, K., and Ólavsdóttir, J.: An overview of the Upper Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region, Geol. Soc. Spec. Publ., 447, 11–68, https://doi.org/10.1144/sp447.2, 2016.

Straneo, F., Sutherland, D. A., Holland, D., Gladish, C., Hamilton, G. S., Johnson, H. L., Rignot, E., Xu, Y., and Koppes, M.: Characteristics of ocean waters reaching Greenland's glaciers, Ann. Glaciol., 53, 202–210, https://doi.org/10.3189/2012AoG60A059, 2017.

Straume, E. O., Gaina, C., Medvedev, S., and Nisancioglu, K. H.: Global Cenozoic Paleobathymetry with a focus on the Northern Hemisphere Oceanic Gateways, Gondwana Res., 86, 126–143, https://doi.org/10.1016/j.gr.2020.05.011, 2020.

Talwani, M. and Eldholm, O.: Evolution of the Norwegian-Greenland Sea, Geol. Soc. Am. Bull., 88, 969–999, https://doi.org/10.1130/0016-7606(1977)88<969:EOTNS>2.0.CO;2, 1977.

Thiede, J., Myhre, A. M., Firth, J. V., Johnson, G. L., and Ruddiman, W. F.: Procedings ODP Scientific Results Ocean Drilling Program, College Station, 1996.

Thiede, J., Jessen, C., Knutz, P., Kuijpers, A., Mikkelsen, N., Nørgaard-Pedersen, N., and Spielhagen, R. F.: Millions of years of Greenland ice sheet history recorded in Ocean sediments, Polarforschung, 80, 141–159, http://hdl.handle.net/10013/epic.38391.d001 (last access: June 2023), 2010.

Tripati, A. K., Eagle, R. A., Morton, A., Dowdeswell, J. A., Atkinson, K. L., Bahé, Y., Dawber, C. F., Khadun, E., Shaw, R. M. H., Shorttle, O., and Thanabalasundaram, L.: Evidence for glaciation in the Northern Hemisphere back to 44 Ma from ice-rafted debris in the Greenland Sea, Earth Planet. Sc. Lett., 265, 112–122, https://doi.org/10.1016/j.epsl.2007.09.045, 2008.

Tsikalas, F., Faleide, J. I., Eldholm, O., and Antonio Blaich, O.: The NE Atlantic conjugate margins, in Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps, Elsevier, 140–201, https://doi.org/10.1016/b978-0-444-56357-6.00004-4, 2012.

Våge, K., Pickart, R. S., Spall, M. A., Moore, G. W. K., Valdimarsson, H., Torres, D. J., Erofeeva, S. Y., and Nilsen, J. E. Ø.: Revised circulation scheme north of the Denmark Strait, Deep-Sea Res. Pt. I, 79, 20–39, https://doi.org/10.1016/j.dsr.2013.05.007, 2013.

van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change, The Cryosphere, 10, 1933–1946, https://doi.org/10.5194/tc-10-1933-2016, 2016.

White, R. S., Bown, J. W., and Smallwood, J. R.: The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges, J. Geol. Soc., 152, 1039–1045, https://doi.org/10.1144/gsl.jgs.1995.152.01.26, 1995.

Wolf, T. C. W. and Thiede, J.: History of terrigenous sedimentation during the past 10 m.y. in the North Atlantic (ODP Legs 104 and 105 and DSDP Leg 81), Mar. Geol., 101, 83–102, https://doi.org/10.1016/0025-3227(91)90064-B, 1991.

Wright, J. D. and Miller, K. G.: Control of North Atlantic Deep Water circulation by the Greenland-Scotland Ridge, Paleocoanography, 11, 157–170, 1996.

Zwally, H. J., Giovinetto, M. B., Beckley, M. A., and Saba, J. L.: Antarctic and Greenland Drainage Systems, GSFC Cryospheric Sciences Laboratory, https://earth.gsfc.nasa.gov/cryo/data/polar-altimetry/antarctic-and-greenland-drainage-systems (last access: June 2023), 2012.

Sci. Dril., 33, 47–65, 2024
https://doi.org/10.5194/sd-33-47-2024
© Author(s) 2024. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

Workshop Reports

Paleogene Earth perturbations in the US Atlantic Coastal Plain (PEP-US): coring transects of hyperthermals to understand past carbon injections and ecosystem responses

Marci M. Robinson[1], Kenneth G. Miller[2], Tali L. Babila[3], Timothy J. Bralower[4], James V. Browning[2], Marlow J. Cramwinckel[5], Monika Doubrawa[6], Gavin L. Foster[7], Megan K. Fung[8], Sean Kinney[2], Maria Makarova[9], Peter P. McLaughlin[10], Paul N. Pearson[11], Ursula Röhl[12], Morgan F. Schaller[13], Jean M. Self-Trail[1], Appy Sluijs[4], Thomas Westerhold[12], James D. Wright[2], and James C. Zachos[14]

[1]Florence Bascom Geoscience Center, U.S. Geological Survey, Reston, VA 22032, USA
[2]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08534, USA
[3]Earth, Environmental, and Planetary Sciences, Case Western Reserve University, Cleveland, OH 44106, USA
[4]Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA
[5]Department of Earth Sciences, Faculty of Geosciences, Utrecht University, 3584 CB, Utrecht, the Netherlands
[6]Earth and Environmental Sciences, KU Leuven, Leuven, 3001, Belgium
[7]School of Ocean and Earth Science, University of Southampton, Southampton, SO14 3ZH, UK
[8]Earth and Environmental Sciences, California Lutheran University, Thousand Oaks, CA 91360, USA
[9]independent researcher: 283 Newark Ave., Apt. 4R, Jersey City, NJ 07302, USA
[10]Delaware Geological Survey, University of Delaware, Newark, DE 19716, USA
[11]Department of Earth Sciences, University College London, London, WC1E, 6BT, UK
[12]MARUM – Center for Marine Environmental Sciences, University of Bremen, 28359 Bremen, Germany
[13]Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[14]Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA

Correspondence: Marci M. Robinson (mmrobinson@usgs.gov)

Received: 6 November 2023 – Revised: 9 February 2024 – Accepted: 12 February 2024 – Published: 2 April 2024

Abstract. The release of over 4500 Gt (gigatonnes) of carbon at the Paleocene–Eocene boundary provides the closest geological analog to modern anthropogenic CO_2 emissions. The cause(s) of and responses to the resulting Paleocene–Eocene Thermal Maximum (PETM) and attendant carbon isotopic excursion (CIE) remain enigmatic and intriguing despite over 30 years of intense study. CIE records from the deep sea are generally thin due to its short duration and slow sedimentation rates, and they are truncated due to corrosive bottom waters dissolving carbonate sediments. In contrast, PETM coastal plain sections along the US mid-Atlantic margin are thick, generally having an expanded record of the CIE. Drilling here presents an opportunity to study the PETM onset to a level of detail that could transform our understanding of this important event. Previous drilling in this region provided important insights, but existing cores are either depleted or contain stratigraphic gaps. New core material is needed for well-resolved marine climate records. To plan new drilling, members of the international scientific community attended a multi-staged, hybrid scientific drilling workshop in 2022 designed to maximize not only scientifically and demographically diverse participation but also to protect participants' health and safety during the global pandemic and to reduce our carbon footprint. The resulting plan identified 10 sites for drill holes that would penetrate the Cretaceous–Paleogene (K–Pg) boundary, targeting the pre-onset excursion (POE), the CIE onset, the rapidly deposited Marlboro Clay that records a very thick CIE body, and other Eocene hyperthermals. The workshop participants developed several primary scientific objectives related to investigating the nature and the cause(s) of the CIE onset as well as the biotic effects of the PETM on the

paleoshelf. Additional objectives focus on the evidence for widespread wildfires and changes in the hydrological cycle, shelf morphology, and sea level during the PETM as well as the desire to study both underlying K–Pg sediments and overlying post-Eocene records of extreme hyperthermal climate events. All objectives address our overarching research question: what was the Earth system response to a rapid carbon cycle perturbation?

1 Introduction

Despite over 30 years of intense study since rapid climatic and biotic change during the Paleocene–Eocene Thermal Maximum (PETM) was first identified (Thomas, 1989; Kennett and Stott, 1991), the cause(s) of and responses to the PETM and attendant stable carbon isotope excursion (CIE) in the global exogenic carbon pool (e.g., Koch et al., 1992; Dickens et al., 1995) remain enigmatic and intriguing. The PETM remains an essential target of climate study, as the release of over 4500 Gt (with Gt = Pg; Gutjahr et al., 2017) of carbon at the Paleocene–Eocene (P–E) boundary provides the closest geological analog to modern anthropogenic CO_2 emissions (e.g., Pagani et al., 2006; Zeebe et al., 2016). The PETM was characterized by a global temperature increase of about 5 °C (Kennett and Stott, 1991; Koch et al., 1992; Bralower et al., 1995; Thomas et al., 1999; Zachos et al., 2003; Tripati and Elderfield, 2004; Sluijs et al., 2006; Dunkley Jones et al., 2013; Tierney et al., 2022). The CIE is recorded by a δ^{13}C decrease in marine (∼ 2 ‰–3 ‰ in benthic; ∼ 2.5 ‰–4 ‰ in planktonic foraminifera) and terrestrial (∼ 2.5 ‰–7 ‰) environments, requiring a substantial addition of ^{13}C-depleted carbon into global reservoirs (Kennett and Stott, 1991; Zachos et al., 2007; McInerney and Wing, 2011; Koch et al., 1992; Wing et al., 2005; Bowen et al., 2015). The initiation of the CIE is used to correlate the beginning of the Eocene epoch (∼ 56 Ma).

The PETM CIE can be subdivided into three stages (Röhl et al., 2007; Fig. 1). The first is the CIE onset and a subsequent sharp δ^{13}C decrease, the rapidity of which is still unresolved (e.g., Kennett and Stott, 1991; Bowen et al., 2015; Kirtland Turner and Ridgwell, 2016; Zeebe et al., 2016, Babila et al., 2022; Li et al., 2022). The onset duration estimates range widely (e.g., Cui et al., 2011; Wright and Schaller, 2013), though recent estimates indicate that it occurred in less than 4 kyr (Kirtland Turner, 2018). The second stage, the CIE body (Röhl et al., 2007), is a period of relatively stable low carbon isotope values with astronomical tuning-based estimates on the order of 40 to 100 kyr (Katz et al., 1999; Röhl et al., 2007; Westerhold et al., 2018). The third stage is the gradual exponential recovery period of ∼ 70 to 140 kyr to near pre-CIE δ^{13}C values (Dickens et al., 1997; Katz et al., 1999; Röhl et al., 2007; Westerhold et al., 2018), although several records suggest a faster recovery for at least part of the event (e.g., Bowen and Zachos, 2010). Following the PETM, about 20 smaller negative δ^{13}C excursions (e.g., H1, H2, I1, I2, J, K, L; ∼ 54–53 Ma) occurred in the early Eocene. Several of these have been shown to reflect transient global warming phases ("hyperthermals"; Thomas and Zachos, 2000), such as Eocene Thermal Maximum (ETM) 2 (e.g., Lourens et al., 2005; Sluijs et al., 2009). All the Paleogene CIEs, possibly except for the PETM, were astronomically paced, reflecting continued climate instability in this high CO_2 world (e.g., Cramer et al., 2003; Westerhold et al., 2017; Setty et al., 2023).

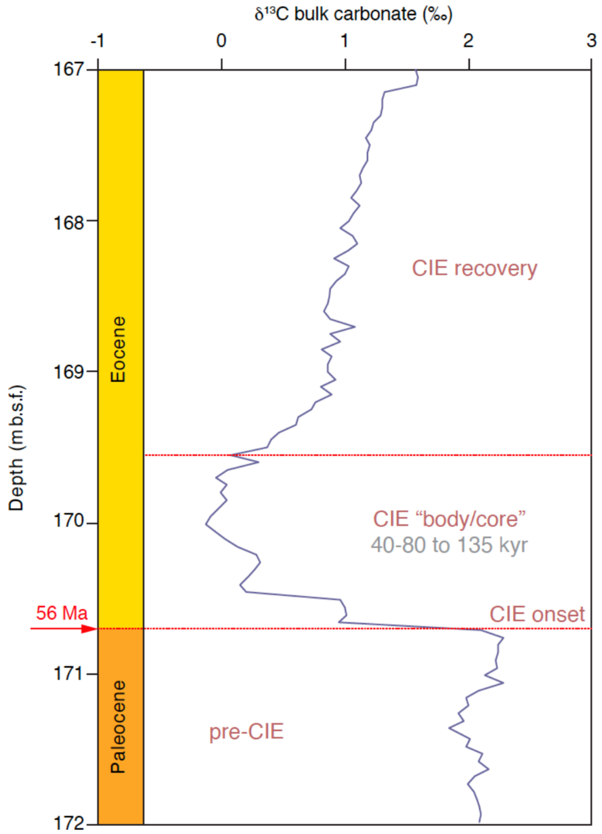


Figure 1. Anatomy of the carbon isotope excursion (CIE) using the bulk carbonate δ^{13}C record of Bains et al. (1999) from ODP Site 690, Weddell Sea. This classic deep-sea PETM record illustrates the shape, sediment thickness, and duration of the CIE onset, body/core, and recovery.

Deep-sea sections recording the PETM and other Paleogene hyperthermals are generally thin (< 1 m) due to their geologically short durations and typical deep-sea sedimentation rates of 1–2 cm kyr^{-1} (Dickens et al., 1995; Westerhold et al., 2018). Records of the CIE onset and body in deep-sea sediments are also generally truncated owing to the corrosive conditions in bottom waters at the onset of the PETM, causing dissolution of calcium carbonate sediments on the seafloor (Zachos et al., 2005; Colosimo et al., 2005; Bralower et al., 2014). In contrast, thick marine sections (> 15 m) recording the CIE occur in the US mid-Atlantic Coastal Plain in New Jersey, Maryland, Delaware, and Virginia. These sections generally have an expanded CIE onset in updip sites, an expanded CIE body in medial sites, and an expanded CIE recovery in the downdip sites due to progradation of sediments (Fig. 2; Podrecca et al., 2021).

The prospect of drilling these coastal plain deposits to access data from the expanded PETM sediments led to an International Continental Scientific Drilling Program (ICDP) workshop in 2022, entitled "Coring Paleocene-Eocene Thermal Maximum transects, mid-Atlantic U.S. Coastal Plain: Constraining timing and cause of carbon injection and ecosystem response". The multi-staged, hybrid scientific drilling workshop was designed to maximize not only scientifically and demographically diverse participation but also to protect participants' health and safety during the global pandemic and to reduce the carbon footprint of this well-attended, international event. This hybrid workshop included (1) a half-day interactive and recorded webinar (22 June, virtually and at Rutgers University, New Brunswick, New Jersey, USA) devoted to discussions related to the science of the PETM and a presentation of potential drill sites; (2) two townhall meetings (24 August, at MARUM, University of Bremen, Germany, during the 12th Climatic and Biotic Events of the Paleogene (CBEP12) conference and 31 August at Grieghallen, Bergen, Norway, during the International Conference in Paleoceanography (ICP14)) where presentations of the preliminary drilling plan and a summary of scientific topics engaged and encouraged additional participation; and (3) a hybrid workshop (17 November, virtually and at Rutgers University, New Brunswick, New Jersey, USA) that finalized the drilling plan and assembled international, discipline-based research teams for post-drilling science.

2 US mid-Atlantic Coastal Plain sediments

Across the US mid-Atlantic Coastal Plain, the PETM is associated with the Marlboro Clay, a unique geologic formation of laminated dark gray silty clay. The sediments surrounding the Marlboro Clay, however, vary geographically (Fig. 3). In New Jersey, the lowermost Eocene Marlboro Clay conformably overlies normal sequences of quartzose silty glauconitic sand to glauconitic silt of the Paleocene Vincentown Formation deposited in inner to middle neritic environments (∼ 25–50 m; Harris et al., 2010). The Marlboro Clay is disconformably overlain by either green carbonate clays of the Manasquan Formation or a return to glauconitic sandy silts that are indistinguishable from the Vincentown Formation. In Maryland and Virginia, the Marlboro Clay overlies the greenish-black to greenish-gray very fine to coarse glauconitic sands of the Paleocene Aquia Formation, deposited in inner to middle neritic environments (Gibson and Bybell, 1994). The Aquia Formation–Marlboro Clay contact, coinciding with the Paleocene–Eocene boundary, is usually sharp and highly burrowed, though in New Jersey it is gradational. In Virginia and Maryland, the Marlboro Clay is disconformably overlain by the Nanjemoy Formation, which is lithologically like the Aquia Formation. Previous drilling in Delaware has not identified the presence of the Marlboro Clay, but data presented at the workshops predict a significant thickness near the Maryland border.

The Marlboro Clay has a high kaolinite content (Gibson et al., 1993, 2000; Cramer et al., 1999; Lombardi, 2013) that was initially thought to reflect a more vigorous hydrological cycle due to expanded humid tropical conditions during the PETM (Gibson et al., 1993). However, $\delta^{18}O$ studies of the clays suggest the kaolinite is recycled from older strata (Kopp et al., 2009; John et al., 2012). The Marlboro Clay also contains magnetic grains like those produced by magnetotactic bacteria on the Amazon shelf and preserved in suboxic zones (Lippert and Zachos, 2007; Kopp et al., 2009), but the dominant source of the magnetic assemblage appears to be non-biotic (Kent et al., 2003, 2017; Wang et al., 2013). The Marlboro Clay, both in composition and flux delivered to the paleoshelf is unusual in the Cenozoic sedimentological history of the US Atlantic Coastal Plain.

The Marlboro Clay was deposited in waters mostly deeper than storm wave base. Exceptions are preserved in updip strata in Virginia and Maryland that record current or storm-wave activity in ripple cross-laminated fine silts that locally exhibit scour and fill channels (Mixon et al., 2000) and the preservation of delta features (Self-Trail et al., 2017). In New Jersey, the Marlboro Clay was deposited in middle to outer neritic paleodepths, primarily on clinoform foresets (Fig. 2; Lombardi, 2013; Stassen et al., 2015; Podrecca et al., 2021). The modern Amazon shelf has been cited as an analog setting for the deposition of the Marlboro Clay (Kopp et al., 2009), exhibiting rapid (2–10 $cm\,yr^{-1} = 2000$–$10\,000\,cm\,kyr^{-1}$) deposition by fluid mud in a subaqueous delta with a clinoform geometry (Nittrouer et al., 1996). The Marlboro Clay contains depositional features consistent with the dominance of fluidized mud depositional processes, including the lack of bioturbation and the rapid burial of vertically oriented pieces of woody debris (Fig. 4). Extremely rapid sediment accumulation (up to 2000 $cm\,yr^{-1}$) has been suggested in some intervals (Wright and Schaller, 2013) with the Wilson Lake Hole B sediments indicating that the basal Marlboro Clay represents a very brief interval with anomalously high sedimentation rates (> 12–24 $cm\,yr^{-1}$; Miller et al., 2017; Doubrawa et al., 2022). The rate of deposition likely varies across the paleoshelf, and though still not fully quantified, was 1 or 2 orders of magnitude higher than that of concurrent sediments in the deep sea.

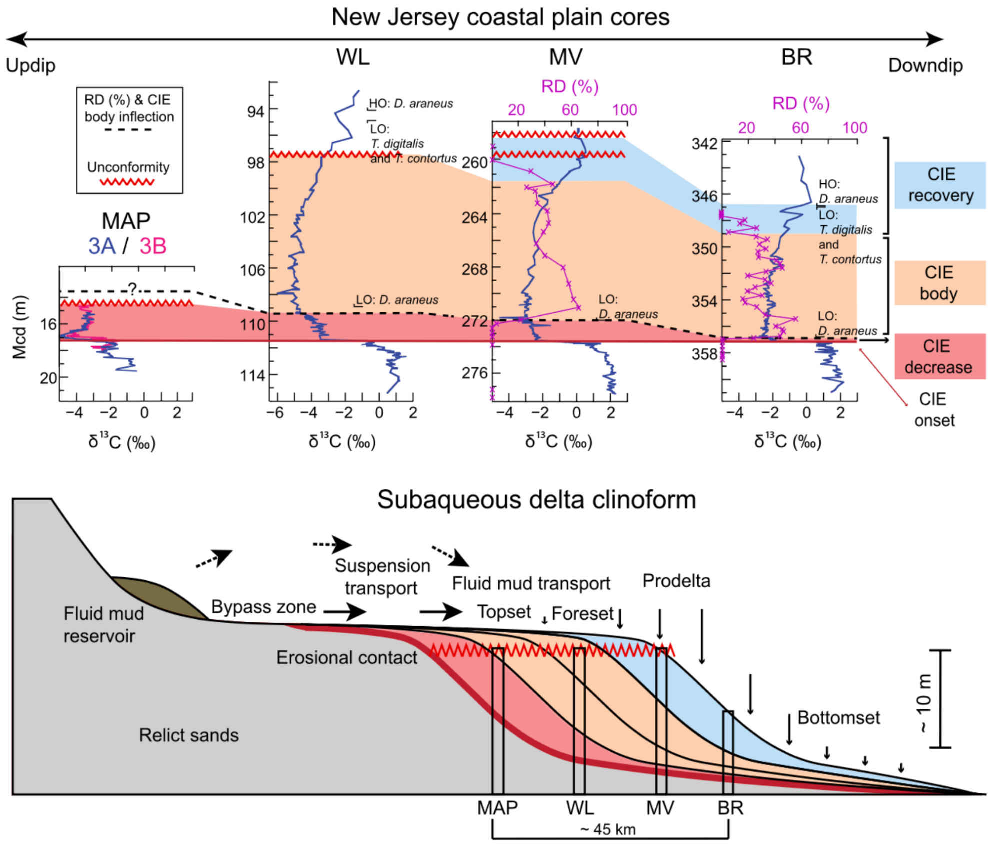


Figure 2. (Top) Bulk δ^{13}C records across the four New Jersey coastal plain sites: Medford Auger Project (MAP; 3A in blue and 3B in pink); Wilson Lake B (WL; Wright and Schaller, 2013), Millville (MV; Makarova et al., 2017), and Bass River (BR; Cramer et al., 1999; John et al., 2008); *%Rhomboaster–Discoaster* (RD; Harris et al., 2010 [MV and BR]; Miller et al., 2017 [WL]); benthic biostratigraphy (Stassen et al., 2015). Records are aligned on the CIE onset (red line), correlated with biostratigraphy, and presented with uniform vertical scale. (Bottom) Idealized subaqueous delta clinoform depositional model depicting fluid mud reservoir source bypassing shallow zones and rapidly building foresets in a prodelta environment. Red saw-toothed line denotes the unconformity capping the top of the Marlboro Clay. Figure from Podrecca et al. (2021).

3 Existing PETM climate records from the US mid-Atlantic Coastal Plain

Previous U.S. Geological Survey (USGS), Ocean Drilling Program (ODP), and Rutgers University coastal plain drilling (Fig. 5) has provided a wealth of basic information and important clues as to the cause(s) of and responses to the PETM. Many USGS cores containing PETM deposits (e.g., Cambridge–Dorchester Airport, Mattawoman Creek–Billingsley Road (MCBR), Randalls Farm, South Dover Bridge, and Wilson Lake Hole A cores) were drilled over the last several decades mainly for the purposes of coastal plain mapping, and their utility for climate studies was only more recently realized. ODP Leg 174AX (e.g., Ancora, Bass River, Millville, Sea Girt cores), similarly, was initially designed to better understand the sequence distribution and architecture of the paleoshelf and slope but also returned PETM sediments that have been key to our present understanding of this interval. The more recent USGS cores (Howards Tract, Knapps Narrows), however, were drilled for climate study as part of the USGS Eocene Hyperthermals Project. Likewise, Wilson Lake Hole B and the Medford Auger Project (Medford core) expressly addressed PETM CIE climate objectives. These more recent efforts represent the beginning of the new phase of PETM climate research on the mid-Atlantic Coastal Plain.

The CIE onset occurs in these cores at the contact between the upper Paleocene Aquia Formation or Vincentown Formation and the lowermost Eocene Marlboro Clay. In the most landward sites in New Jersey and Maryland, the δ^{13}C values across the P–E boundary depict a gradual transition (Self-Trail et al., 2017), but a carbonate dissolution zone in the basal Marlboro Clay found at many deeper sites, possibly due to lysocline shoaling (Bralower et al., 2018), precludes stable isotope records at the contact. However, a 2 ‰ δ^{13}C decrease and ocean acidification event that slightly predates the PETM (the pre-onset excursion or POE; Bowen et al., 2015) records an early pulse of PETM-like conditions in the South Dover

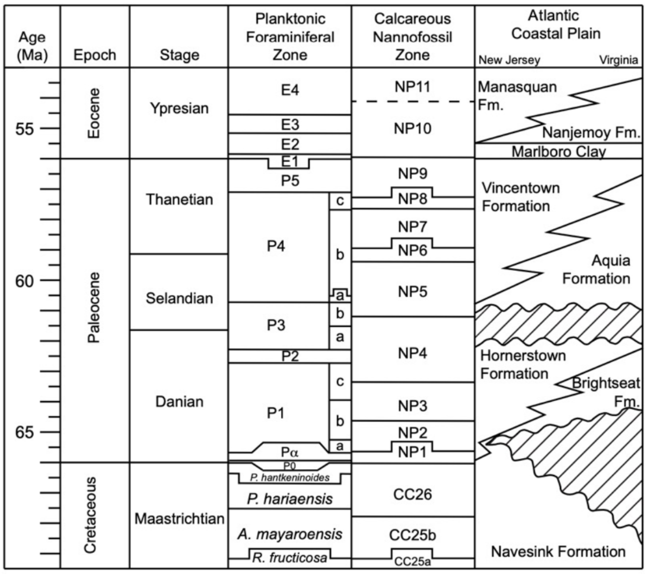


Figure 3. Stratigraphic column showing Cretaceous, Paleocene, and Eocene planktonic foraminiferal and calcareous nannofossil zones and geological formation names on the US mid-Atlantic Coastal Plain. Note that same-age sediments in Virginia and New Jersey have different formation names above and below the Marlboro Clay. The Marlboro Clay is closely associated with the PETM across the US mid-Atlantic Coastal Plain.

Bridge core (Robinson and Spivey, 2019; Babila et al., 2022; Doubrawa et al., 2022), and several smaller CIEs following the PETM are recorded in Maryland (Rush et al., 2023), Virginia, and New Jersey (Fung et al., 2023) sediments. Together, these Eocene hyperthermals provide insight into tipping points in the ecosystem response to rapid change.

One goal of PETM climate research is to place constraints on the timing, magnitude, and tempo of carbon release(s) at the CIE onset (and POE events) and investigate their relationship to each other. However, at Bass River in New Jersey, similar to the deep-ocean records, single-foraminifer stable carbon and oxygen isotope populations are bimodal, showing no intermediate values (Zachos et al., 2007; John et al., 2008) and indicating that foraminifer accumulation rates or foraminifer preservation were insufficient to capture the timescale of ^{13}C-depleted carbon injection. At Mattawoman Creek–Billingsley Road (MCBR), the sedimentation rates are relatively higher than at Bass River, but the foraminifers available for stable isotopic measurements were very small and rare, and many samples were barren (Self-Trail et al., 2017). Foraminifera were more abundant at South Dover Bridge, and δ^{11}B provided a pH proxy, offering a way to trace carbon injection directly (Fig. 6; Babila et al., 2022) but only outside the dissolution zone. The POE was accompanied by a drop in pH and possibly a rise in temperature like during the main CIE (Babila et al., 2022) but was much shorter lived ($\sim$2 kyr; Bowen et al., 2015), explaining why deep-sea records fail to capture it. The relatively low deep-sea sedimentation rates and severe chemical erosion at the onset of the main CIE yield insufficient temporal coverage to resolve such a short-lived event. Unfortunately, current late Paleocene stratigraphic age control is poor, and duration estimates between the upper boundary of the POE and main CIE range from 1000 years to 100 kyr (Babila et al., 2022; Doubrawa et al., 2022), limiting our ability to evaluate the connectedness of the multiple carbon injections to the PETM onset.

Another goal is to determine if biotic change, sea surface warming, and the carbon injection associated with the POE were concurrent. Initial micropaleontological and TEX_{86} studies at Bass River and Wilson Lake (Sluijs et al., 2007) and micropaleontological studies of South Dover Bridge and MCBR (Self-Trail et al., 2017; Robinson and Spivey, 2019; Doubrawa et al., 2022) suggest that biotic change and warming lead the CIE onset by a few millennia. The precursor warming was later reproduced in other regions (e.g., Secord et al., 2010; Frieling et al., 2019). However, TEX_{86} records from the Medford Auger Project suggest that warming was coincident with or lags the CIE onset (Makarova, 2018; Inglis et al., 2023). Several studies show a gradual, precursor δ^{13}C decrease below the sharp CIE (Miller et al., 2017), with a thickness that increases landward (Fig. 2; Podrecca et al., 2021). Whether temperature rise triggered the carbon release at the POE and main PETM remains an open question.

Irrespective of timing, excess carbon and excessive temperatures affected the ecosystem across the PETM. I/Ca measurements suggest widespread deoxygenation of thermocline and bottom waters (Zhou et al., 2014; Makarova, 2018), high surface temperatures may have caused the exclusion of eukaryotes in surface waters (Aze et al., 2014; Frieling et al., 2017, 2018; Makarova et al., 2017; Si and Aubry, 2018), and an unusual nannofossil assemblage suggests biotic stress due to photic zone acidification (Kahn and Aubry, 2004; Bralower et al., 2018). Planktonic and benthic organisms showed a significant extinction (benthos) and showed both ecophenotypic (plankton) and ecological (benthos and plankton) responses to the PETM on the paleoshelf, but the cause of the changes is debated.

These ecosystem perturbations are evident on a global scale but can be addressed using records from the US mid-Atlantic Coastal Plain. For example, Makarova et al. (2017) used the transect afforded by Wilson Lake, Ancora, Millville, and Bass River to evaluate two scenarios: (1) a change in the water column structure and (2) a change in habitat or seasonality of the surface dwellers. Si and Aubry (2018) favored a habitat (migration) change, while Makarova (2018) argued for a change in seasonality consistent with the eukaryote exclusion hypothesis. Benthic foraminiferal assemblages suggest dysoxia with an opportunistic CIE fauna (Stassen et al., 2012, 2015; Robinson and Spivey, 2019). I/Ca data from benthic taxa suggest decreased oxygen concentration but not full anoxia in bottom waters (Makarova, 2018), support-

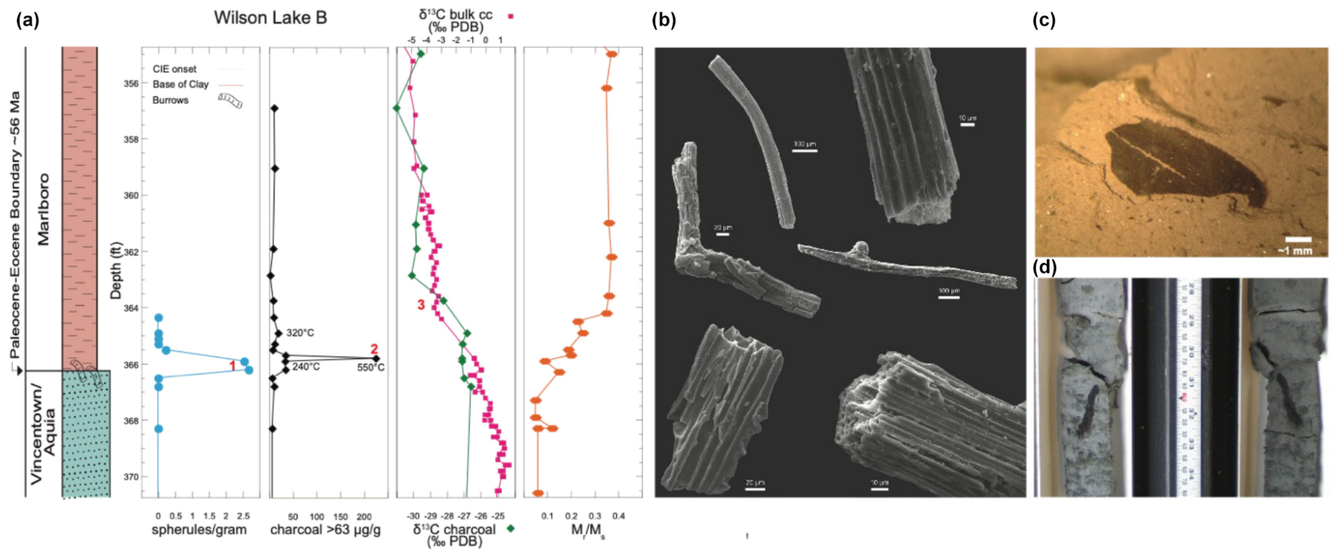


Figure 4. **(a)** Charcoal abundance (no. $> 63\,\mu m\,g^{-1}$) and $\delta^{13}C_{charcoal}$ (Fung et al., 2019) plotted with $\delta^{13}C_{bulk}$ carbonate and impact spherules per gram discovered at Wilson Lake (Schaller et al., 2016). Ratio of saturation remanence to saturation magnetization (M_r/M_s) at Wilson Lake is interpreted as having been generated by soil pyrogenesis (Kent et al., 2017). **(b)** SEM images of charcoal fragments recovered from Randalls Farm and Wilson Lake cores from Fung et al. (2019). **(c)** Photograph of intact leaf fragments from Randalls Farm (Schaller and Fung, 2018). **(d)** Photograph of split core at Wilson Lake showing upright twig; scale at center.

ing additional low-oxygen evidence from planktonic/benthic ratios and benthic foraminifera assemblages (Stassen et al., 2012). In addition, reconstructions of paleowater depth based on lithofacies models (Browning et al., 2006), benthic foraminiferal assemblages (Stassen et al., 2015; Robinson and Spivey, 2019), ostracod eye size (Tian et al., 2022), and water depth preferences of planktonic foraminifera (Robinson and Spivey, 2019) indicate a relative sea level rise across the CIE onset that is difficult to explain if ice-free conditions are assumed.

Current available observations of global environmental and ecosystem changes suggest a greater severity both in magnitude and spatial coverage at the PETM when compared to the POE and other Eocene hyperthermals. Two potential causes for a more substantial climate system response proposed are related to external forcing of the carbon cycle. One is related to the release of volcanic carbon inputs, mainly as CO_2 associated with the North Atlantic Igneous Province, and preliminary results from drilling on the Norwegian margin strongly supports a link (Planke et al., 2022). The other is extraterrestrial impact. The discovery of in situ impact spherules at the CIE onset at Millville, Wilson Lake, Medford, and deep-sea ODP Site 1051 (Fig. 7; Schaller et al., 2016) offers an intriguing link between extraterrestrial impact and the PETM. The Ar–Ar age of the spherules is indistinguishable from its depositional age at the P–E boundary (Schaller and Fung, 2018; Schaller et al., 2019), indicating that it is not reworked from another impact event. If proximal to the crater, the relatively low abundance of spherules at the CIE onset implies that the volume of CO_2 released by this impact was probably not significant. The possibility of a larger impactor cannot be excluded until the ejecta is identified at more far-field P–E sites, though even a small impact could provide a carbon release trigger related to wildfires (Kent et al., 2017; Schaller and Fung, 2018) or earthquakes releasing slope methane (Katz et al., 1999). Fung et al. (2019) documented abundant charcoal in a distinct peak within the CIE onset (Fig. 4) in New Jersey (Wilson Lake) and Virginia (Randalls Farm). Vitrinite reflectance shows that the hottest fires occurred within the peak of charcoal abundance, suggesting they were unusual against the background fire regime of the mid-Atlantic Coastal Plain. These data are tantalizing evidence that, whatever the trigger, wildfires were intense and possibly widespread at the beginning of the PETM climate change. Again, continued research to refine the ages of these sediments would help to understand the cause(s) of the PETM and various environmental perturbations associated with the event onset.

In summary, previously drilled cores on the US mid-Atlantic Coastal Plain have provided important clues toward understanding the cause and nature of global change at the PETM, but major open questions still remain. These concern the timing, magnitude, tempo of, and relationship between carbon releases; lead–lag relationships between biotic change and warming and the CIE onset; and the more substantial climate system response of the CIE compared to the POE. These questions can only be fully addressed with additional cores.

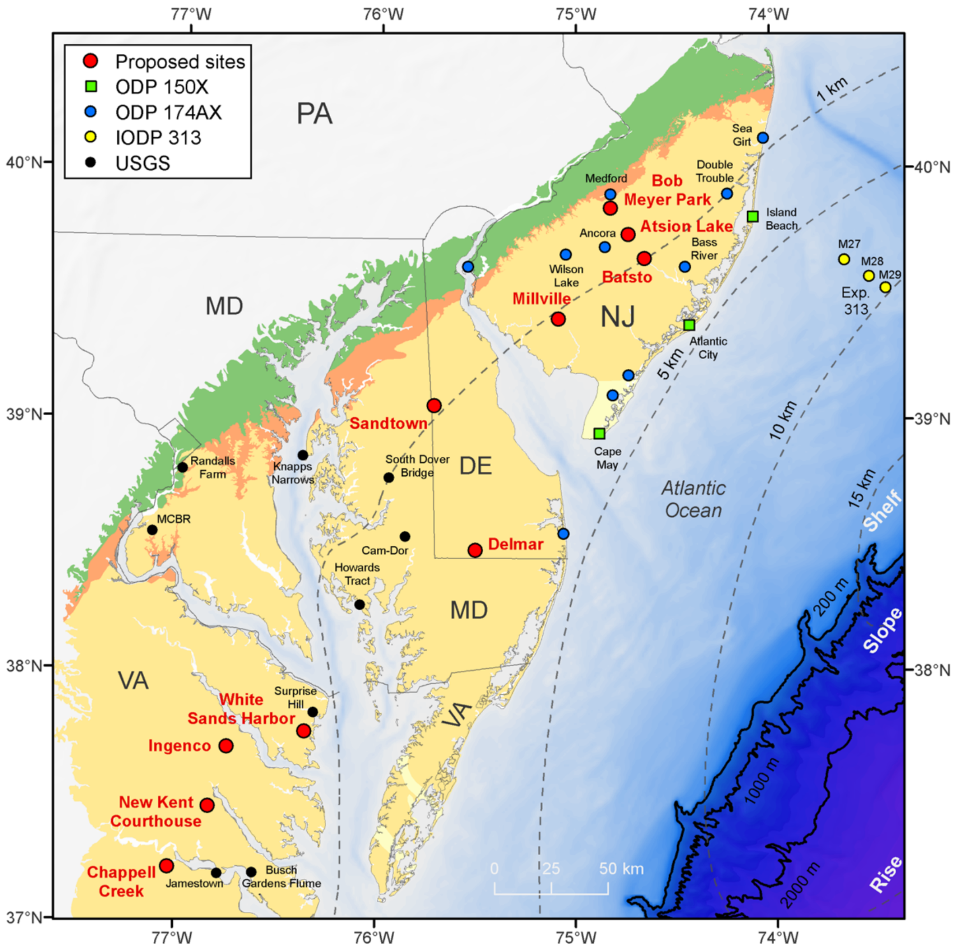


Figure 5. Geological map of the US mid-Atlantic Coastal Plain (NJ, New Jersey; DE, Delaware; MD, Maryland; and VA, Virginia) with proposed core sites (red circles) and locations of existing ODP, IODP, and USGS cores. Cam-Dor represents Cambridge–Dorchester Airport; MCBR represents Mattawoman Creek–Billingsley Road. Colors represent outcrops of Cretaceous (green), Paleogene (peach), Neogene (medium yellow), and Quaternary (light yellow) sediments. Blue shades are proportional to water depth. Dashed contours are depth to basement (in km) indicating the direction of dip of sedimentary deposits.

4 Proposed drill sites

The PETM deposits on the US mid-Atlantic Coastal Plain have the potential to provide unparalleled resolution of the shallow marine POE, PETM, and subsequent Eocene hyperthermals. Considering local tectonics and how coastal zone dynamics likely affected PETM deposition, workshop participants designed a drilling campaign of 10 drill holes, with four in New Jersey, two near the Delaware–Maryland border, and four in Virginia, that are intended to capture these events in high resolution (Fig. 5; Table 1). We have assembled extensive well log data for New Jersey, Delaware–Maryland, and Virginia that allow us to confidently predict the presence of the Marlboro Clay (Crider et al., 2022, 2023). Closely spaced well log data are superior to seismic profiling for our purposes because of the thinness (15 m) of the target interval and the fact that it is not imaged on high-resolution 2D and 3D data offshore. We have used existing core holes and well logs from observation wells to construct isopach maps to predict the thickness of the PETM section and to precisely target the proposed core holes in New Jersey and Maryland.

In addition to the PETM and POE, this coring campaign targets Eocene hyperthermals and the K–Pg boundary. Previous coastal plain drilling of ODP Leg 174AX documented the validity of the transect approach (Miller et al., 2017), but existing cores are not adequate for further study. Firstly, the previous cores were drilled for sea-level, hydrostratigraphic, and geologic mapping studies that require less core material for descriptive work than detailed temporal paleoceanographic studies. Bass River and Millville cores, for example, are largely depleted due to intense community sampling of both the working and archive halves, and Wilson Lake Hole B is nearly depleted. Secondly, critical regions from the shallowest paleodepth were either not cored or the sediments were diagenetically altered. Thirdly, unlike ICDP projects and IODP expeditions, no concerted effort was made to co-

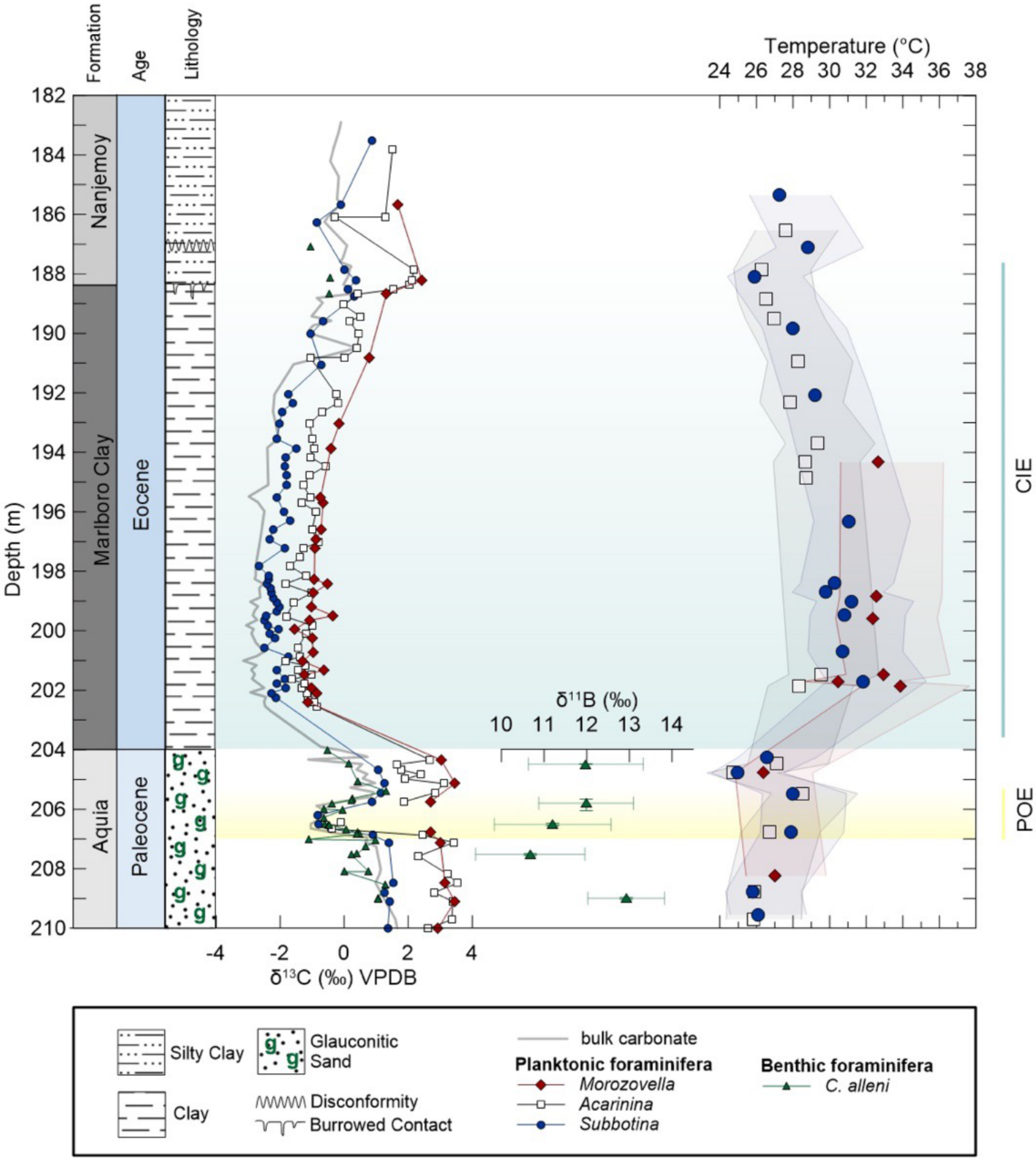


Figure 6. South Dover Bridge (SDB) carbon isotope ($\delta^{13}C$) bulk carbonate, planktonic, and benthic foraminifera records. Planktonic foraminifera Mg/Ca estimated ocean temperatures and error envelope include uncertainty in Mg/Ca seawater composition. Average $\delta^{11}B$ of single-specimen benthic foraminifera (*Cibicidoides alleni*), with 2 SE associated with the mean for each depth and the uncertainty in our internal reference material. Vertical error bars of $\delta^{11}B$ represent the full sample depth range of the multiple individual measurements represented by the average $\delta^{11}B$ value. Highlighted in yellow is the POE and in blue is the body of the CIE. Note the expanded (> 16 m thick) CIE body compared to < 2 m thickness at ODP Site 690 in Fig. 1 and the dissolution zone (area of no data) at the base of the Marlboro Clay. Figure from Babila et al. (2022).

ordinate community study or sampling and storing of the PETM intervals.

Therefore, new cores are required to support further PETM research and broaden the potential application of new analyses. New cores will replace existing New Jersey cores that are largely depleted and will supplement the cores currently available in Maryland and Virginia. The southerly of the core sites in Delaware will investigate the record of the PETM between the Maryland-Virginia sites and New Jersey, closer to the core of the Salisbury Embayment. New drilling will complete the depth transects across the paleoshelf (Fig. 5), which is necessary to sample the complex patchwork of sediment and to fully exploit the potential to produce climate records. We will recover the large core volumes that are required for multi-proxy studies and will employ modern high-stratigraphic/temporal-resolution core scanning techniques

Table 1. Proposed drill site locations and estimated depth to 3 m below K–Pg.

Location	State	Latitude	Longitude	Target core depth (m)
Bob Meyer Park	New Jersey	39.84539° N	74.82048° W	52
Atsion Lake	New Jersey	39.73989° N	74.72925° W	134
Batsto	New Jersey	39.64387° N	74.64678° W	300
Millville	New Jersey	39.40476° N	75.08851° W	318
Sandtown	Delaware	39.04040° N	75.71468° W	227
Delmar	Delaware	38.51140° N	75.55390° W	399
White Sands Harbor	Virginia	37.94104° N	76.33889° W	199
Ingenco	Virginia	37.43867° N	77.12799° W	141
New Kent Courthouse	Virginia	37.50804° N	76.98473° W	107
Chappell Creek	Virginia	37.28818° N	77.21100° W	46

that are required for astronomical chronology and to resolve environmental changes. Fresh, non-oxidized cores less affected by post-drilling carbonate dissolution will provide the opportunity for additional proxy analyses not possible on existing material (e.g., organic biomarker analysis, inspection of the CIE onset interval for spherules and foraminiferal tests).

4.1 New Jersey

The Marlboro Clay is found in two sediment lobes in New Jersey, indicative of two sediment sources. Our four proposed cores, Millville, Bob Meyer Park in Medford, Atsion Lake, and Batsto, will form a dip transect across the larger, thicker southern lobe from clinoform topset to toes using the predictions of Podrecca et al. (2021; Fig. 2). The existing Millville core is depleted in the onset interval. Therefore, we propose to redrill Millville, a critical location because it provides the most complete CIE onset amongst current mid-Atlantic Coastal Plain core archives and therefore of broad interest to the PETM community. The Medford Auger Project (Podrecca et al., 2021) recovered cores over a 1 km transect near Marlboro Clay outcrops with an expanded CIE onset section. We propose drilling 5.2 km downdip from this transect at Bob Meyer Park in Medford and 19 km downdip at Atsion Lake to recover an expanded CIE onset and to constrain inner shelf conditions. Batsto is 31 km downdip and provides a location between these sites and the existing Bass River site (45 km downdip from outcrop) to record the most expanded CIE body and middle shelf conditions. Bob Meyer Park, Atsion, and Batsto provide an ideal depth transect, with Millville along-strike of Batsto (Fig. 5).

4.2 Delaware–Maryland

The greatest thickness of Paleogene and Neogene sediments lies in the Delmarva Peninsula near Salisbury, Maryland, and these sediments have been largely uncored. Drilling near the Delaware–Maryland border will provide a new wealth of subsurface data. We propose a drill site at Delmar, Delaware, to target the thickest and deepest water deposits sampled in the region. Based on well logs from Federalsburg, Maryland, we predict a thick (>15 m) PETM section. We also propose an updip site at Sandtown, Delaware, to test the updip extent of the Marlboro Clay. Drilling at the two Delmarva sites, Sandtown and Delmar (Fig. 5), will provide an excellent opportunity for exploratory studies where there is a current knowledge gap and where the nature of the Paleocene–Eocene boundary is not understood.

4.3 Virginia

We used data from numerous wells (i.e., geophysical logs, descriptions of cuttings) to predict the presence and thickness of the Marlboro Clay in Virginia with high confidence. We propose a drill site in White Sands Harbor where Virginia Department of Environmental Quality well data record 67 ft (20 m) of Marlboro Clay. This would represent the thickest Marlboro Clay in the region. Three additional proposed sites at Ingenco, New Kent Courthouse, and Chappell Creek subdivision, with Marlboro Clay thicknesses predicted to be 28 ft (9 m), 30 ft (9 m), and 20 ft (6 m), respectively, will form a deepwater transect that complements existing USGS cores at Surprise Hill, Busch Gardens Flume, and Jamestown (Fig. 5).

5 Drilling plan challenges

Our drilling plan incorporating new material from New Jersey, Delaware, Maryland, and Virginia to complement existing material represents the best opportunity to study the PETM and other hyperthermals in high resolution. The level of detail prescribed in our research approach (see Sect. 6) will transform our understanding of these important events. Our plan, however, is not free from uncertainties and challenges. Differential preservation and patchwork distribution of PETM sediments is expected in coastal plain deposits and can be difficult to predict due to the discontinuous nature of

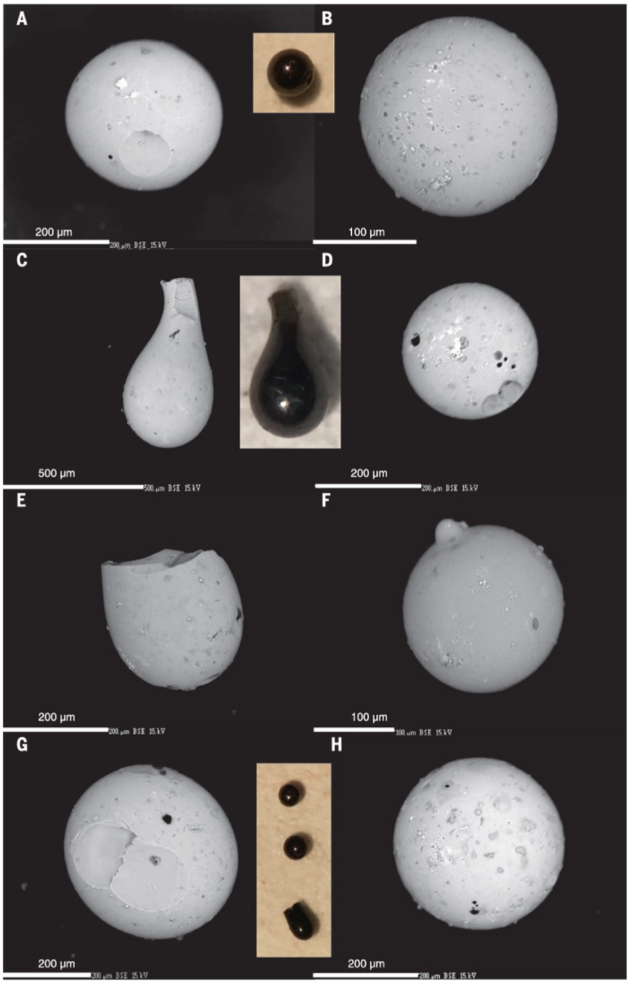


Figure 7. Electron backscatter (15 kV) images of representative P–E spherules from IODP Hole 1051B, Wilson Lake B, and Millville cores and the Medford exposure. Selected color micrographs are shown as insets. **(a)** Microtektite with a surface pit from ODP Hole 1051B. **(b)** Microkrystite from IODP Hole 1051B. **(c)** Teardrop-shaped glass spherule from Millville; inset is photomicrograph of same object. **(d)** Microkrystite with surface pit from Millville. **(e)** Broken drop-form or dumbbell from Wilson Lake B. **(f)** Microtektite from Wilson Lake B with a smaller spherule accreted to the side. **(g)** Microtektite with surface microcrater from the Medford, New Jersey, exposures. Inset shows several other forms found at Medford, which allows us to exclude drilling contamination as a source of the spherules. **(h)** Typical microkrystite from Wilson Lake B. Figure from Schaller et al. (2016).

coastal zone sedimentation and erosion. Different intervals of PETM deposition are expected at different locations, depending on the coastal zone dynamics unique to each site. Also, age control is historically challenging in coastal plain sediments due to the generally sparse nature of the microfossils traditionally used for biostratigraphy and stable isotope analyses. Despite these challenges, coastal plain sediments are excellent snapshots of extreme climate states and contain valuable quantitative paleoecological data from peak warm periods. In addition, the preservation of calcium carbonate microfossils is exceptional compared to the deep-sea section due to the dominant clay content limiting dissolution and diagenetic alteration (Pearson et al., 2001).

The biostratigraphic record of Rush et al. (2023; Fig. 8) illustrates the differences in sedimentation rate and preservation of strata at Maryland sites, including the effects of local faulting. Though the US mid-Atlantic coast is a passive continental margin dominated by thermal subsidence and loading, faulting has been mapped in Maryland and Virginia. In some cores, faulting and subsequent erosion is responsible for the absence of some PETM sediments (e.g., in the Knapps Narrows core; Fig. 8). Though there is little evidence of faulting in the New Jersey sections, the US mid-Atlantic margin is affected on the several-million-year scale by relative uplift and subsidence due to changes in mantle dynamic topography (Moucha et al., 2008; Schmelz et al., 2021).

Predicting the nature of sediments to be drilled is always challenging. In the mid-Atlantic Coastal Plain, no seismic profiles are available for a site survey, but seismic profiling is not the best way to detect the ~ 15 m thick targets at depth. Instead, we have used existing core holes and well logs from observation wells to predict the thickness of the PETM section and to precisely target the proposed core holes in New Jersey and Virginia. On the other hand, while well data control is limited near the proposed Delaware–Maryland sites, drilling here will provide an excellent opportunity for exploratory studies. These sites admittedly pose the greatest risk of missing our target strata, but they also offer the most potential to gain new information.

Finally, age control can be difficult in coastal plain sediments. One fundamental goal is to establish the stratigraphic framework of the coastal plain sediments and to correlate them between and among sites. Core descriptions and age control will provide the basis for all further analyses. Bulk $\delta^{13}C$ records, zircon and apatite geochronology, and X-ray fluorescence (XRF) scans will provide a means of evaluating equivalency on the transects. The impact spherules can serve as an isochronous marker horizon to compare between sites. Coupled with careful sedimentologic and stratigraphic documentation, this will enable analyses of the nature, timing, and duration of the PETM onset, our primary science focus.

6 Shallow marine records of Paleocene to Eocene global climate and ecosystem perturbations – research approach and science questions

The PETM, POE, and Eocene hyperthermals provide an excellent template for evaluation of the Earth system response to rapid carbon release at varying degrees of global warming under different background climate states during the Paleogene. The targeted sedimentary strata will allow for evaluation of leads vs. lags in the climate system across a regional

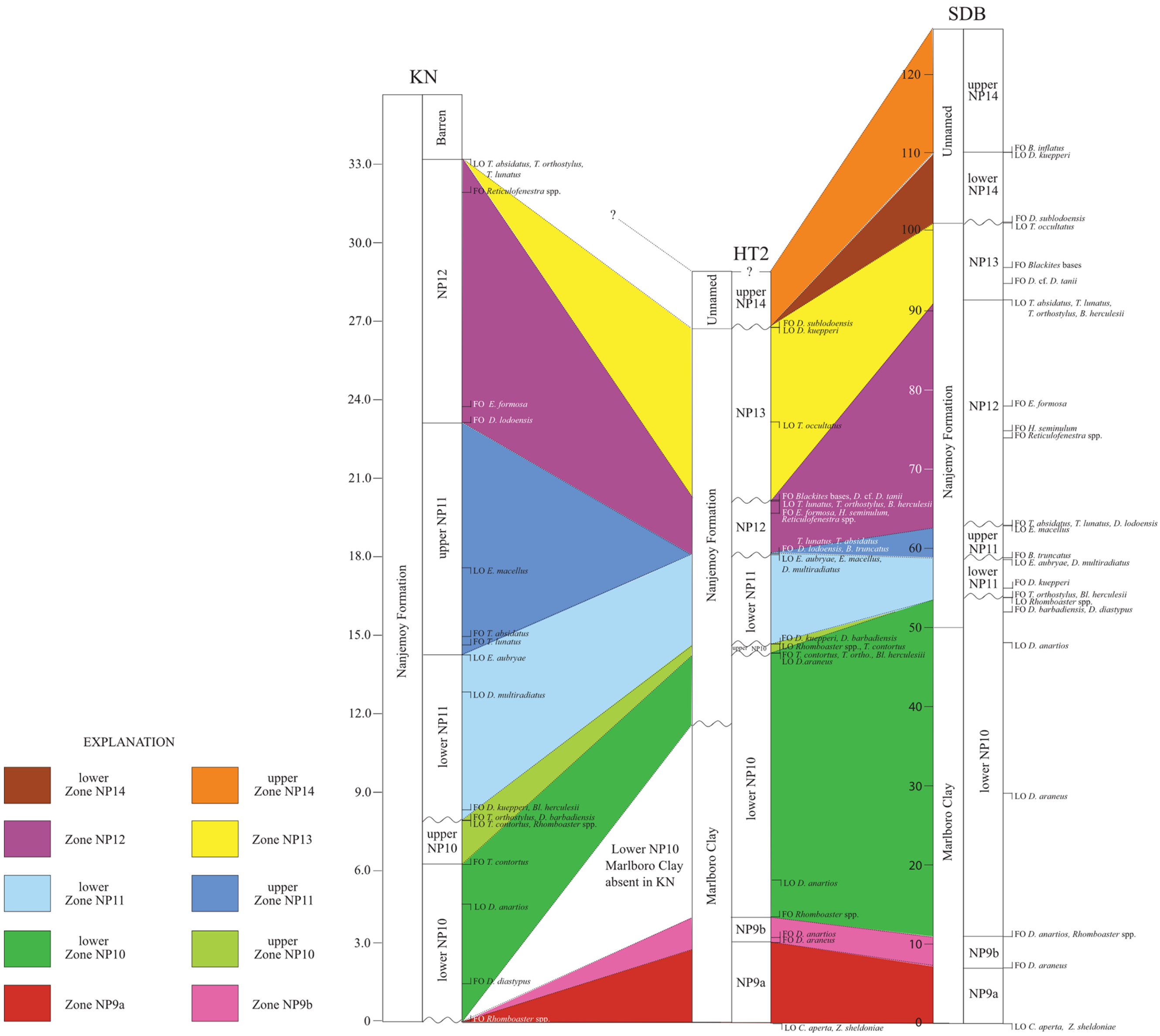


Figure 8. Regional calcareous nannofossil biostratigraphy. NP represents nannofossil zones; KN represents Knapps Narrows; HT2 represents Howards Tract 2; SDB represents South Dover Bridge. Thickness of sediments in each core is shown in meters from the base of the PETM. Figure from Rush et al. (2023).

scale transect of the mid-latitudes during these differing intervals of rapid global warming. Given the very high temporal resolution (sub-millennial scale), the material to be recovered by the drilling campaign is uniquely situated to answer several questions with direct relevance to anthropogenic climate change. Our overarching question asks: what was the Earth system response to rapid carbon cycle perturbations?

6.1 What was the nature of the CIE onset?

The Marlboro Clay and the transition to it from the underlying units represents a period of unequivocally rapid deposition that provides an expanded record of the carbon release(s) at the PETM onset. Still unknown is the nature of the heterogeneity in the CIE magnitude across shelf deposits, and estimates of the CIE onset duration are wide-ranging. Sampling the transition zone and Marlboro Clay will allow for testing of contrasting hypotheses: one proposing that the main CIE carbon release was virtually instantaneous (Wright and Schaller, 2013) and the other suggesting that it was protracted over ∼ 4 kyr (Kirtland Turner, 2018; Pearson and Nicholas, 2013; Pearson and Thomas, 2015; Zeebe et al., 2016; Li et al., 2022). New cores will provide material needed to attain exceptional resolution of the CIE onset and will be evaluated to determine the speed of the onset and also any lead–lag relationships of carbon injection, temperature rise, biotic and sedimentation change, and extraterrestrial impacts.

Although the POE has been observed in a number of locations, questions remain about the full magnitude of the carbon isotope excursion, whether the carbon released was regional or global, and if it was one or multiple carbon injections that preceded the main CIE or merely a consequence of bioturbation or some other artifact. By measuring stable isotopes in foraminifera, including single-specimen analyses, from several sections on transects across the shelf, we will constrain the true size of the POE, regional expression, and stratigraphic coherence relative to the main CIE. This relative role of forcings and feedbacks is critical in understanding the rate and mechanism(s) of carbon released at the PETM. In addition, we will investigate the relationship between the POE, the CIE recorded at the PETM onset, and the Eocene hyperthermals. We will target sediments likely to contain the POE to determine its relationship to the CIE onset and if it is global and isochronous with previous POE observations from terrestrial records, as well as whether it was a unique event or if there is evidence for multiple carbon injections being responsible for warming at the PETM.

We also propose to determine the origin of the low carbonate and generally carbonate fossil-free interval during the CIE onset (Fig. 6) and how that affects its characterization. We will do this by testing the hypotheses that the carbonate free interval is due to (1) ocean acidification and/or carbonate compensation depth shoaling into the photic zone, (2) dilution by massive input of terrigenous silty clays, or (3) the absence of eukaryotic phytoplankton due to extreme temperatures and ecological exclusion. Our transect approach sampling different paleodepths (nearshore, middle, and outer paleoshelf) in three settings (New Jersey, Delaware–Maryland, and Virginia) will yield constraints at different sites, quantifying dissolution, dilution, and abundance of eukaryotic phytoplankton (foraminifera, nannofossils, and dinoflagellates).

6.2 What was the cause of the CIE onset?

All Eocene hyperthermals initiated during maxima in orbital eccentricity, but whether or not the PETM did is still under debate (Cramer et al., 2003; Zachos et al., 2010; Zeebe and Lourens, 2019; Li et al., 2022; Piedrahita et al., 2022). An orbital trigger superimposed on the long-term late Paleocene-early Eocene warming trend might also be consistent with the magnitude difference between the PETM and subsequent smaller hyperthermals (e.g., Lunt et al., 2011), although the PETM remains exceptionally large. Mathematical analyses on deep-ocean foraminifer δ^{13}C and δ^{18}O records suggest a loss of Earth system resilience in the run-up to the PETM, ETM2, and ETM3, suggesting a carbon source that can be perturbed with climate and carbon cycle variability at the Earth's surface (Setty et al., 2023). But which mechanisms were in place and what was the potential role of North Atlantic Igneous Province volcanisms and even impacts? If the CIE onset occurred during an eccentricity maximum, this may have enhanced the sensitivity of the system to greenhouse gas forcing. The POE and other (biotic) precursors to the CIE may be indicators of an unstable climate system, characterized by a loss of resilience, with a subsequent larger response (the PETM) to a lesser forcing (Setty et al., 2023; Armstrong McKay and Lenton, 2018). We will test the hypothesis that an impact triggered carbon release that, in concert with a preconditioned system and possible astronomical forcing, resulted in a large carbon cycle event. Widespread wildfires associated with an impact would have been synchronous throughout the region. We will test the relationships among carbon release, impact, and wildfires by evaluating the relationships among δ^{13}C, charcoal occurrences, and microtektites.

6.3 What were the biotic effects of the CIEs on the paleoshelf?

We will quantify the severity of the biotic effects of the PETM, POE, and Eocene hyperthermals on the paleoshelf and attempt to recognize ecological tipping points. We will test the hypotheses that there was widespread deoxygenation of the thermocline and bottom waters, an absence of eukaryotes in surface waters due to excessive temperature, and photic zone acidification and biotic stress. The debate surrounding these hypotheses highlights a need for greater community involvement through common study of a series of cores containing nannofossils, planktonic and benthic foraminifera, and dinoflagellate cysts. The proposed transects will allow for a comparison between the degree of biotic effects latitudinally and across a range of water depths. The Paleocene and Eocene shelf sections will provide a detailed and high-resolution baseline for paleoenvironmental conditions, placing POE, PETM, and Eocene hyperthermal excursions into geological context. Establishing the background variability of paleoshelf environments (providing a baseline of the background) is essential to establishing thresholds that cause a major biotic response. Though orbital and other forcings cause hyperthermals, ecological tipping points affect the biotic response, with smaller events causing little disruption and major events like the PETM and ETM2 causing major disruptions.

6.4 How was the hydrological cycle affected by PETM and other hyperthermal perturbations?

We will test whether the intensification of the hydrologic cycle, particularly the increase in seasonality (Rush et al., 2021), drove increased sedimentation or if increased sediment input was due to impact and wildfires in the hinterland. Our drilling will improve estimates of the volume of terrestrial sediments deposited on the shelf, and analyses of hydrogen isotopes of leaf wax *n*-alkanes will help to reconstruct hydrological cycling. These estimates will be essential for validating hydrologic cycle models of the PETM and testing depositional models. Terrestrial PETM investigations will also benefit from drilling in the coastal plain, as this shallow marine environment provides direct linkages between marine and terrestrial responses to the K–Pg, PETM, and Eocene hyperthermals. Vimpere et al. (2023) provided evidence for continental-scale paleodrainage changes in response to the PETM. Their results from the Gulf of Mexico suggest a strong sedimentary response to changes in the hydrological cycle and also the tectonic regimes that propagated over North America. Mineralogical and isotopic analyses sampling different Marlboro Clay sediment lobes (depocenters) will constrain the provenance of the Marlboro Clay. Did the Potomac, Susquehanna, and Delaware paleorivers tap different Appalachian source regions? We will also consider tectonic-focused studies that examine the potential for the rejuvenation of relief in the Appalachians during the Neogene, as recorded by proxies for chemical weathering in coastal plain sediments.

6.5 How much did relative sea level rise across the PETM?

Multiple lines of evidence argue for a large relative sea level rise in this region across the PETM (Browning et al., 2006; Stassen et al., 2015; Robinson and Spivey, 2019; Tian et al., 2022). We assume that the fall line, the western boundary of the Atlantic Coastal Plain, approximates the shoreline during the late Paleocene and early Eocene, as this is the extent of marine deposits, but the amount of relative sea level rise in the southern (e.g., Virginia) and northern (e.g., New Jersey) regions is not well constrained nor is the relationship between regional and global mean sea level rise (Sluijs et al., 2008). We will use two-dimensional backstripping to reconstruct the paleoslope and place water-depth estimates into a geological context using both inverse techniques (Steckler et al., 1999) and the forward model of Schmelz et al. (2024). We will test our forward model with reconstructions of paleowater depth based on lithofacies models, benthic foraminiferal assemblages, ostracod eye size, and water depth preferences of planktonic foraminifera. Our paleoslope modeling, validating, and refining will be critical in evaluating the response across the paleoshelf to the major warming events of the POE, PETM, and Eocene hyperthermals. Our modeling will also allow us to test the role of changes in global mean sea level versus mantle dynamic topography in controlling deposition during the largely ice-free world of the Paleocene to early Eocene and subsequent development of middle Eocene to Oligocene ice sheets (Miller et al., 2020; Schmelz et al., 2021).

6.6 Can we detect K–Pg seiche influence or warming due to Deccan volcanism?

Because most of the lower Paleocene is condensed or missing, our PETM drilling places us within 30 m of potentially complete K–Pg marine records. By extending our drilling by 30 m, we will be able to test the hypothesis that K–Pg seiche/tsunami wave influence was restricted to paleodepths of ∼ 60 m or less and that deeper sites contain in situ deposits with ballistic ejecta. Previous studies have established Bass River, New Jersey, as a world-class location to sample ballistic ejecta from the K–Pg boundary (Olsson et al., 1997, 2002; Esmeray-Senlet et al., 2015, 2017), and we plan to sample through the K–Pg boundary in our core holes. The mid-Atlantic Coastal Plain offers sampling of intermediate field response (e.g., Schulte et al., 2010) to the K–Pg impact with evidence of seiche/swash back deposits. The most downdip site (Bass River) provides a record of deposition of undisturbed spherule ballistic ejecta immediately following impact (Olsson et al., 1997). Intermediate sites (e.g., Ancora) contain reworked spherules and evidence of seiche/swash back deposits, whereas the most updip sites are either diastemic or have iridium at lower concentration over intervals of tens of centimeters due to bioturbation (Esmeray-Senlet et al., 2015, 2017). The proposed Atsion site is likely to recover seiche/swash back deposits, and the proposed Batsto site should provide a continuous record like Bass River. These cores should recover evidence of the latest Maastrichtian warming event associated with Deccan volcanism ∼ 300 kyr before the K–Pg boundary (e.g., Barnet et al., 2018); this warming was recorded and calibrated to magnetostratigraphy at Bass River (Olsson et al., 2002). A high-resolution record from the uppermost Cretaceous could inform whether this event caused significant ecosystem changes prior to the asteroid impact. The K–Pg will not be sampled in Maryland and Virginia sites where the upper Cretaceous and lower Danian is truncated, and we suspect that it is similarly truncated in Delaware.

6.7 What can we learn from post-Eocene climate records?

Post-Eocene sediments will be of value to ongoing studies focused on the Late Pliocene and Middle Miocene, intervals of past global warmth that are similar to our modern climate in terms of the rate of change and/or the magnitude of atmospheric CO_2 concentration and average global temperature. The mid-Piacenzian warm period (∼ 3.3 to 3.0 Ma) during the Late Pliocene represents a final warm pulse before Earth's climate deteriorated into Pleistocene glacial–interglacial cycles, and the Miocene Climatic Optimum (∼ 17–15 Ma) was a warm period atop an already warm climate, similar to our current warming. Climate transitions into the mid-Piacenzian warm period (rapid warming at ∼ 3.3–3.2 Ma) and out of the Miocene Climatic Optimum (slow cooling during the Middle Miocene Climate Transition; ∼ 15–13 Ma) are also valuable targets as they represent rapid changes in global temperature, sea level, ice volume, and oceanic circulation. Previous analyses from the mid-Atlantic Coastal Plain indicate that various foraminifer and biomarker-based proxies provide high-quality reconstructions for these time periods (de Bar et al., 2019; Dowsett et al., 2021; Robinson et al., 2022).

7 Summary

The Paleocene–Eocene Thermal Maximum (PETM) is an essential target of climate study because it is the closest geological analog to modern anthropogenic CO_2 emissions. Even after decades of study, however, the cause(s) of and responses to the PETM remain enigmatic and intriguing. Because the rate of deposition of the PETM sediments on the US mid-Atlantic shelf was at least an order of magnitude higher than that of concurrent sediments in the deep sea, coastal plain sediments have the potential to resolve centennial and up to decadal climatic variability and to provide exceptional (sub-millennial) temporal resolution. The discontinuous nature of coastal sedimentation, however, requires numerous sites to constrain events like the POE, PETM, and Eocene hyperthermals.

Workshop participants identified 10 sites for PETM drill holes that target the POE, the CIE onset, the rapidly deposited Marlboro Clay, and other Eocene hyperthermals. To reduce the uncertainty in recovering our target interval, we used data from existing core holes and extensive well logs to construct isopach maps and precisely target thick PETM sections in eight of the proposed core holes. Drilling two cores where little data are available will provide an excellent opportunity to gain pioneering new information. In our post-drilling research, we will not only address the PETM as the most prominent carbon isotope excursion and carbon release of the Cenozoic, but we will also address multiple examples of rapid warming in the latest Paleocene to early Eocene. Though the PETM is arguably the best analog to our rapidly warming climate, the POE and early Eocene hyperthermals provide additional points of comparison for other anthropogenic carbon emission scenarios. Each provides valuable insights into different Earth system responses and feedbacks.

Data availability. Well log data used to predict the presence of the Marlboro Clay in Maryland and Virginia can be found in a U.S. Geological Survey Data Release at https://doi.org/10.5066/P9AHP9BC (Crider et al., 2022). ODP Leg 150X and ODP Leg 174X data used to predict Marlboro Clay thickness in New Jersey are available through the ODP website. Additional well log data for New Jersey and Delaware are unpublished and reside at Rutgers University and with the New Jersey and Delaware state geological surveys.

Author contributions. MMR and KGM prepared the workshop report with contributions from all co-authors.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher’s note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. We acknowledge ICDP for funding the workshop entitled “Coring Paleocene–Eocene Thermal Maximum transects, mid-Atlantic U.S. Coastal Plain: Constraining timing and cause of carbon injection and ecosystem response”. We thank Rutgers University and the organizers of the 12th Climatic and Biotic Events of the Paleogene (CBEP12) conference at MARUM, University of Bremen, and the International Conference in Paleoceanography (ICP14) at Grieghallen, Bergen, for hosting the in-person components of our workshop. Finally, we thank Brian Huber and Christian Zeeden for providing insightful reviews that improved the quality of the paper.

Review statement. This paper was edited by Ulrich Harms and reviewed by Brian Huber and Christian Zeeden.

References

Armstrong McKay, D. I. and Lenton, T. M.: Reduced carbon cycle resilience across the Palaeocene–Eocene Thermal Maximum, Clim. Past, 14, 1515–1527, https://doi.org/10.5194/cp-14-1515-2018, 2018.

Aze, T., Pearson, P. N., Dickson, A. J., Badger, M. P. S., Bown, P. R., Pancost, R. D., Gibbs, S. J., Huber, B. T., Leng, M. J., Coe, A. L., Cohen, A. S., and Foster, G. L.: Extreme warming of tropical waters during the Paleocene–Eocene Thermal Maximum, Geology, 42, 739–742, https://doi.org/10.1130/G35637.1, 2014.

Babila, T. L., Penman, D. E., Standish, C. D., Doubrawa, M., Bralower, T. J., Robinson, M. M., Self-Trail, J. M., Speijer, R. P., Stassen, P., Foster, G. L., and Zachos, J. C.: Surface ocean warming and acidification driven by rapid carbon release precedes Paleocene-Eocene Thermal Maximum, Science Advances, 8, eabg1025, https://doi.org/10.1126/sciadv.abg1025, 2022.

Bains, S., Corfield, R. M., and Norris, R. D.: Mechanisms of climate warming at the end of the Paleocene, Science, 285, 724–727, https://doi.org/10.1126/science.285.5428.724, 1999.

Barnet, J. S. K., Littler, K, Droon, D., Leng, M. J., Westerhold, T., Rohl, U., and Zachos, J. C.: A new high-resolution chronology for the late Maastrichtian warming event: Establishing robust temporal links with the onset of Deccan volcanism, Geology, 46, 147–150, https://doi.org/10.1130/G39771.1, 2018.

Bowen, G. J. and Zachos, J. C.: Rapid carbon sequestration at the termination of the Palaeocene-Eocene Thermal Maximum, Nat. Geosci., 3, 866–869, 2010.

Bowen, G. J., Maibauer, B. J., Kraus, M. J., Röhl, U., Westerhold, T., Steimke, A., Gingerich, P.D., Wing, S. L., and Clyde, W. C.: Two massive, rapid releases of carbon during the onset of the Palaeocene–Eocene thermal maximum, Nat. Geosci., 8, 44–47, https://doi.org/10.1038/ngeo2316, 2015.

Bralower, T. J., Zachos, J. C., Thomas, E., Parrow, M., Paull, C. K., Kelly, D. C., Premoli Silva, I., Sliter, W. V., and Lohmann, K. C.: Late Paleocene to Eocene paleoceanography of the equatorial Pacific Ocean: stable isotopes recorded at Ocean Drilling Program Site 865, Allison Guyot, Paleoceanography, 10, 841–865, https://doi.org/10.1029/95PA01143, 1995.

Bralower, T. J., Kelly, D. C., Gibbs, S., Farley, K., Eccles, L., Lindemann, T. L., and Smith, G. J.: Impact of dissolution on the sedimentary record of the Paleocene–Eocene thermal maximum, Earth Planet. Sc. Lett., 401, 70–82, https://doi.org/10.1016/j.epsl.2014.05.055, 2014.

Bralower, T. J., Kump, L. R., Self-Trail, J. M., Robinson, M. M., Lyons, S., Babila, T., Ballaron. E., Freeman, K. H., Hajek, E., Rush, W., and Zachos, J. C.: Evidence for shelf acidification during the onset of the Paleocene-Eocene Thermal Maximum, Paleoceanography and Paleoclimatology, 33, 1408–1426, https://doi.org/10.1029/2018PA003382, 2018.

Browning, J. V., Miller, K. G., McLaughlin, P. P., Kominz, M. A., Sugarman, P. J., Monteverde, D., Feigenson, M. D., and Hernàndez, J. C.: Quantification of the effects of eustasy, subsidence, and sediment supply on Miocene sequences, Mid-Atlantic margin of the United States, Geol. Soc. Am. Bull., 118, 567–588, https://doi.org/10.1130/B25551.1, 2006.

Colosimo, A. B, Bralower, T. J., and Zachos, J. C.: Evidence for lysocline shoaling at the Paleocene/Eocene Thermal Maximum on Shatsky Rise, Northwest Pacific, http://www-odp.tamu.edu/publications/198_SR/112/112.htm (last access: 31 January 2024), 2005.

Cramer, B. S., Aubry, M.-P., Miller, K. G., Olsson, R. K., Wright, J. D., and Kent, D. V.: An exceptional chronologic, isotopic, and clay mineralogic record at the latest Paleocene thermal maximum, Bass River, NJ, ODP 174AX, B. Soc. Geol. Fr., 170, 883–897, 1999.

Cramer, B. S., Wright, J. D., Kent, D. V., and Aubry, M.-P.: Orbital climate forcing of δ^{13}C excursions in the late Paleocene–early Eocene (chrons C24n–C25n), Paleoceanography, 18, 1097, https://doi.org/10.1029/2003PA000909, 2003.

Crider, E. A., Self-Trail, J. M., Parker, M., Seefelt, E. L., Staley, A., Beach, T., Bruce, T. S., and Quinn, H.: Database for the isopach map of the Brightseat Formation and structure contour map of the Cretaceous-Paleogene boundary, in Maryland and Virginia, U.S. Geological Survey Data Release [data set], https://doi.org/10.5066/P9AHP9BC, 2022.

Crider, E. A., Self-Trail, J. M., Parker, M., Gardner, K. F., Beach, T., Bruce, T. S., Staley, A., and Quinn, H.: Isopach contour map of the upper Paleocene Aquia Formation and structure contour map of the Paleocene-Eocene boundary in the Salisbury Embayment of Maryland and Virginia, GSA SE/NE Sectional Meeting, Reston, VA, 17–19 March 2023, https://doi.org/10.1130/abs/2023SE-385653, 2023.

Cui, Y., Kump, L. R., Ridgwell, A. J., Charles, A. J., Junium, C. K., Diefendorf, A. F., Freeman, K. H., Urban, N. M., and Harding, I. C.: Slow release of fossil carbon during the Palaeocene–Eocene Thermal Maximum, Nat. Geosci., 4, 481–485, https://doi.org/10.1038/NGEO1179, 2011.

de Bar, M. W., de Nooijer, L. J., Schouten, S., Ziegler, M., Sluijs, A., and Reichart, G.-J.: Comparing Seawater Temperature Proxy Records for the Past 90 Myrs from the Shallow Shelf Record Bass River, New Jersey, Paleoceanography and Paleoclimatology, 34, 455–475, https://doi.org/10.1029/2018PA003453, 2019.

Dickens, G. R., O'Neil, J. R., Rea, D. K., and Owen, R. M.: Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene, Paleoceanography, 10, 965–971, https://doi.org/10.1029/95PA02087, 1995.

Dickens, G. R., Castillo, M. M., and Walker J. C. G.: A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate, Geology, 25, 259–262, https://doi.org/10.1130/0091-7613(1997)025<0259:ABOGIT>2.3.CO;2, 1997.

Doubrawa, M., Stassen, P., Robinson, M. M., Babila, T. L., Zachos, J. C., and Speijer, R. P.: Shelf ecosystems along the U.S. Atlantic Coastal Plain prior to and during the Paleocene-Eocene Thermal Maximum: Insights into the stratigraphic architecture, Paleoceanography and Paleoclimatology, 37, e2022PA004475, https://doi.org/10.1029/2022PA004475, 2022.

Dowsett, H. J., Robinson, M. M., Foley, K. M., and Herbert, T. D.: The Yorktown Formation: Improved Stratigraphy, Chronology, and Paleoclimate Interpretations from the U.S. Mid-Atlantic Coastal Plain, Geosciences, 11, 486, https://doi.org/10.3390/geosciences11120486, 2021.

Dunkley Jones, T., Lunt, D. J., Schmidt, D. N., Ridgwell, A., Sluijs, A., Valdes, P. J., and Maslin, M.: Climate model and proxy data constraints on ocean warming across the Paleocene-Eocene Thermal Maximum, Earth-Sci. Rev., 125, 123–145, https://doi.org/10.1016/j.earscirev.2013.07.004, 2013.

Esmeray-Senlet, S., Wright, J. D., Olsson, R. K., Miller, K. G., Browning, J. V., and Quan, T. M.: Evidence for reduced export productivity following the Cretaceous/-Paleogene mass extinction, Paleoceanography, 30, 1–21, https://doi.org/10.1002/2014PA002724, 2015.

Esmeray-Senlet, S., Miller, K. G., Sherrell, R. M., Senlet, T., and Vellekoop, J., Iridium profiles and delivery across the Cretaceous/Paleogene boundary, Earth Planet. Sc. Lett., 27, 117–126, https://doi.org/10.1016/j.epsl.2016.10.010, 2017.

Frieling, J., Gebhardt, H., Huber, M., Adekeye, O. A., Akande, S. O., Reichart, G.-J., Middelburg, J. J., Schouten, S., and Sluijs, A.: Extreme warmth and heat-stressed plankton in the tropics during the Paleocene-Eocene Thermal Maximum, Science Advances, 3, e1600891, https://doi.org/10.1126/sciadv.1600891, 2017.

Frieling, J., Reichart, G.-J., Middelburg, J. J., Röhl, U., Westerhold, T., Bohaty, S. M., and Sluijs, A.: Tropical Atlantic climate and ecosystem regime shifts during the Paleocene–Eocene Thermal Maximum, Clim. Past, 14, 39–55, https://doi.org/10.5194/cp-14-39-2018, 2018.

Frieling, J., Peterse, F., Lunt, D. J., Bohaty, S. M., Sinninghe Damsté, J. S., Reichart, G.-J., and Sluijs, A.: Widespread warming before and elevated barium burial during the Paleocene-Eocene Thermal Maximum: Evidence for methane hydrate release?, Paleoceanography and Paleoclimatology, 34, 546–566, https://doi.org/10.1029/2018pa003425, 2019.

Fung, M. K., Katz, M. E., Miller, K. G., Browning, J. V., and Rosenthal Y.: Sequence stratigraphy, micropaleontology, and foraminiferal geochemistry, Bass River, New Jersey paleoshelf, USA: Implications for Eocene ice-volume changes, Geosphere, 15, 502–532, https://doi.org/10.1130/GES01652.1, 2019.

Fung, M. K., Katz, M. E., Miller, K. G., Browning, J. V., and Schaller, M. F.: Exploring Early Eocene hyperthermals on the New Jersey paleoshelf (ODP 174AX), J. Foramin. Res., 53, 378–396, https://doi.org/10.2113/gsjfr.53.4.378, 2023.

Gibson, T. G. and Bybell, L. M.: Sedimentary patterns across the Paleocene-Eocene boundary in the Atlantic and Gulf Coastal Plains of the United States, Bulletin – Societe Belge de Geologie, 103, 237–265, 1994.

Gibson, T. G., Bybell, L. M., and Owens, J. P.: Latest Paleocene lithologic and biotic events in neritic deposits from south-western New Jersey, Paleoceanography, 8, 495–514, 1993.

Gibson, T. G., Bybell, L. M., and Mason, D. B.: Stratigraphic and climatic implications of clay mineral changes around the Paleocene/Eocene boundary of the northeastern US margin, Sediment. Geol., 134, 65–92, 2000.

Gutjahr, M., Ridgwell, A., Sexton, P. F., Anagnostou, E., Pearson, P. N., Pälike, H., Norris, R. D., Thomas, E., and Foster, G. L.: Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum, Nature, 548, 573–577, https://doi.org/10.1038/nature23646, 2017.

Harris, A. D., Miller, K. G., Browning, J. V., Sugarman, P. J., Olsson, R. K., Cramer, B. S., and Wright, J. D.: Integrated stratigraphic studies of Paleocene-lowermost Eocene sequences, New Jersey Coastal Plain: Evidence for glacioeustatic control, Paleoceanography, 25, PA3211, https://doi.org/10.1029/2009PA001800, 2010.

Inglis, G. N., Martinez-Sosa, P., Tierney, J. E., Witkowski, C. R., Lyons, S., Baczynski, A. A., and Freeman, K. H.: Impact of organic carbon reworking upon GDGT temperature proxies during the Paleocene-Eocene Thermal Maximum, Org. Geochem., 183, 104644, https://doi.org/10.1016/j.orggeochem.2023.104644, 2023.

John, C. M., Bohaty, S. M., Zachos, J. C., Sluijs, A., Gibbs, S., Brinkhuis, H., and Bralower, T. J.: North American continental margin records of the Paleocene-Eocene thermal maximum: Implications for global carbon and hydrological cycling, Paleoceanography, 23, 1–20, https://doi.org/10.1029/2007PA001465, 2008.

John, C. M., Banerjee, N. R., Longstaffe, F. J., Sica, C., Law, K. R., and Zachos, J. C.: Clay assemblage and oxygen isotopic constraints on the weathering response to the Paleocene- Eocene thermal maximum, east coast of North America, Geology, 40, 591–594, 2012.

Kahn, A. and Aubry, M.-P.: Provincialism associated with the Paleocene/Eocene thermal maximum: temporal constraint, Mar. Micropaleontol., 52, 117–131, https://doi.org/10.1016/j.marmicro.2004.04.003, 2004.

Katz, M. E., Pak, D. K., Dickens, G. R., and Miller, K. G.: The source and fate of massive carbon input during the Latest Paleocene Thermal Maximum, Science, 286, 1531–1533, 1999.

Kennett, J. P. and Stott, L. D.: Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene, Nature, 353, 225–229, 1991.

Kent, D. V., Cramer, B. S., Lanci, L., Wang, D., Wright, J. D., and Van der Voo, R.: A case for a comet impact trigger for the Paleocene/Eocene thermal maximum and carbon isotope excursion, Earth Planet. Sc. Lett., 211, 13–26, 2003.

Kent, D. V., Lanci, L., Wang, H., and Wright, J. D.: Enhanced magnetization of the Marlboro Clay as a product of soil pyrogenesis at the Paleocene–Eocene boundary?, Earth Planet. Sc. Lett., 473, 303–312, https://doi.org/10.1016/j.epsl.2017.06.014, 2017.

Kirtland Turner, S.: Constraints on the onset duration of the Paleocene–Eocene Thermal Maximum, Philos. T. Roy. Soc. A, 376, 20170082, https://doi.org/10.1098/rsta.2017.0082, 2018.

Kirtland Turner, S. and Ridgwell, A.: Development of a novel empirical framework for interpreting geological carbon isotope excursions, with implications for the rate of carbon injection across the PETM, Earth Planet. Sc. Lett., 435, 1–13, https://doi.org/10.1016/j.epsl.2015.11.027, 2016.

Koch, P. L., Zachos, J. C., and Gingerich, P. D.: Correlation between isotope records in marine and continental carbon reservoirs near the Palaeocene/Eocene boundary, Nature, 358, 319–322, 1992.

Kopp, R. E., Schumann, D., Raub, T. D., Powars, D. S., Godfrey, L. V., Swanson-Hysell, N. L., Maloof, A. C., and Vali, H.: An Appalachian Amazon? Magnetofossil evidence for the development of a tropical river-like system in the mid-Atlantic United States during the Paleocene-Eocene thermal maximum, Paleoceanography, 24, 1–17, https://doi.org/10.1029/2009PA001783, 2009.

Li, M., Bralower, T. J., Kump, L. R., Self-Trail, J. M., Zachos, J. C., Rush, W. D., and Robinson, M. M.: Astrochronology of the Paleocene-Eocene thermal maximum on the Atlantic coastal plain, Nat. Commun., 13, 5618, https://doi.org/10.1038/s41467-022-33390-x, 2022.

Lippert, P. C. and Zachos, J. C.: A biogenic origin for anomalous fine-grained magnetic material at the Paleocene–Eocene boundary at Wilson Lake, New Jersey, Paleoceanography, 22, PA4104, https://doi.org/10.1029/2007PA001471, 2007.

Lombardi, C. J.: Lithostratigraphy and clay mineralogy of Paleocene-Eocene thermal maximum sediments at Wilson Lake, NJ, MS thesis, Rutgers University, 94 pp., 2013.

Lourens, L. J., Sluijs, A., Kroon, D., Zachos, J. C., Thomas, E., Röhl, U., Bowles, J., and Raffi, I.: Astronomical pacing of late Palaeocene to early Eocene global warming events, Nature, 435, 1083–1087, https://doi.org/10.1038/nature03814, 2005.

Lunt, D. J., Ridgwell, A., Sluijs, A., Zachos, J., Hunter, S., and Haywood, A.: A model for orbital pacing of methane hydrate destabilization during the Palaeogene, Nat. Geosci., 4, 775–778, 2011.

Makarova, M.: Application of multiproxy tracers to reconstruct paleoenvironmental perturbations on the mid-Atlantic margin across the Paleocene-Eocene thermal maximum, PhD thesis, Rutgers University, 194 pp., https://doi.org/10.7282/t3-k5md-yd57, 2018.

Makarova, M., Wright, J. D., Miller, K. G., Babila, T. L., Rosenthal, Y., and Park, J. I.: Hydrographic and ecologic implications of foraminiferal stable isotopic response across the U.S. mid-Atlantic continental shelf during the Paleocene-Eocene Thermal Maximum, Paleoceanography, 32, 1–18, https://doi.org/10.1002/2016PA002985, 2017.

McInerney, F. A. and Wing, S. L.: The Paleocene-Eocene thermal maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the future, Annu. Rev. Earth Pl. Sc., 39, 489–516, 2011.

Miller, K. G., Browning, J. V., Aubry, M.-P., Babila, T., Baluyot, R. D., Esmeray-Senlet, S., Feigenson, M. D., Karakaya, S., Lombardi, C. J., McCreary, S., McLaughlin. P. P., Monteverde, D. H., Olsson, R. K., Smith C. T., Sugarman., P. J., and Wright J. D.: Wilson Lake B Site, in: Proceedings of the Ocean Drilling Program, edited by: Miller, K. G., Sugarman, P. J., Browning, J. V., McLaughlin, P. P., and Pekar, S. F., Initial reports, Vol. 174AX (Supplement), College Station, TX, https://doi.org/10.2973/odp.proc.174AXS.111.2017, 2017.

Miller, K. G., Browning, J. V., Schmelz, W. J, Kopp, R. E., Mountain, G. S., and Wright, J. D.: Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records, Science Advances, 6, eaaz1346, https://doi.org/10.1126/sciadv.aaz1346, 2020.

Mixon, R. B., Pavlides, L., Powars, D. S., Froelich, A. J., Weems, R. E., Schindler, J. S., Newell, W. L., Edwards, L. E., and Ward, L. W.: Geologic Map of the Fredericksburg 30' x 60' Quadrangle, Virginia and Maryland, U.S. Geological Survey Geologic Investigations Series Map I-2607, scale 1:100,000, 2 sheets, https://doi.org/10.3133/i2607, 2000.

Moucha, R., Forte, A. M., Mitrovica, J. X., Rowley, D. B., Quéré, S., Simmons, N. A., and Grand, S. P.: Dynamic topography and long-term sea-level variations: There is no such thing as a stable continental platform, Earth Planet. Sc. Lett., 271, 101–108, 2008.

Nittrouer, C. A., Kuehl, S. A., Figueiredo Jr., A. G., Allison, M. A., Sommerfield, C. K., Rine, J. M., Faria, L. E. C., and Silveira, O. M.: The geological record preserved by Amazon shelf sedimentation, Cont. Shelf Res., 16, 817–841, 1996.

Olsson, R. K., Miller, K. G., Browning, J. V., Habib, D., and Sugarman, P. J.: Ejecta layer at the Cretaceous-Tertiary boundary, Bass River, New Jersey (Ocean Drilling Program Leg 174AX), Geology, 25, 759–762, 1997.

Olsson, R. K., Miller, K. G., Browning, J. V., Wright, J. D., and Cramer, B. S.: Sequence stratigraphy and sea-level change across the Cretaceous-Tertiary boundary on the New Jersey passive margin, Geological Society of America Special Paper 356, 97–108, https://doi.org/10.1130/0-8137-2356-6.97, 2002.

Pagani, M., Caldeira, K., Archer, D., and Zachos, J. C.: An ancient carbon mystery, Science, 314, 1556–1557, https://doi.org/10.1126/science.1136110, 2006.

Pearson, P. N. and Nicholas, C. J.: Layering in the Paleocene/Eocene boundary of the Millville core is drilling disturbance, P. Natl. Acad. Sci. USA, 111, E1064–E1065, https://doi.org/10.1073/pnas.1322077111, 2013.

Pearson, P. N. and Thomas, E.: Drilling disturbance and constraints on the onset of the Paleocene–Eocene boundary carbon isotope excursion in New Jersey, Clim. Past, 11, 95–104, https://doi.org/10.5194/cp-11-95-2015, 2015.

Pearson, P. N., Ditchfield, P. W., Singano, J., Harcourt-Brown, K. G., Nicholas, C. J., Olsson, R. K., Shackleton, N. J., and Hall, M. A.: Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs, Nature, 413, 481–487, https://doi.org/10.1038/35097000, 2001.

Piedrahita, V. A., Galeotti, S., Zhao, X., Roberts, A. P., Rohling, E. J., Heslop, D., Florindo, F., Grant, K. M., Rodríguez-Sanz, L., Reghellin, D., and Zeebe, R. E.: Orbital phasing of the Paleocene-Eocene Thermal Maximum, Earth Planet. Sc. Lett., 598, 117839, https://doi.org/10.1016/j.epsl.2022.117839, 2022.

Planke, S., Berndt, C., Alvarez Zarikian, C. A., and the Expedition 396 Scientists: Expedition 396 Preliminary Report: Mid-Norwegian continental margin magmatism and paleoclimate implications, International Ocean Discovery Program, https://doi.org/10.14379/iodp.pr.396.2022, 2022.

Podrecca, L. G., Makarova, M., Miller, K. G., Browning, J. V., and Wright, J. D.: Clear as mud: Expanded records of the Paleocene-Eocene Thermal Maximum onset in the Appalachian Amazon, Geology, 49, 1441–1445, https://doi.org/10.1130/G49061.1, 2021.

Robinson, M. M. and Spivey, W. E.: Environmental and geomorphological changes on the eastern North American continental shelf across the Paleocene-Eocene Boundary, Paleoceanography and Paleoclimatology, 34, 715–732, https://doi.org/10.1029/2018PA003357, 2019.

Robinson, M. M., Dowsett, H. J., and Herbert, T. D.: Very high Middle Miocene surface productivity on the U.S. mid-Atlantic shelf amid glacioeustatic sea level variability, Palaeogeogr. Palaeoecol., 606, 111249, https://doi.org/10.1016/j.palaeo.2022.111249, 2022.

Röhl, U., Westerhold, T., Bralower, T. J., and Zachos, J. C.: On the duration of the Paleocene-Eocene thermal maximum (PETM), Geochem. Geophy. Geosy., 8, Q12002, https://doi.org/10.1029/2007GC001784, 2007.

Rush, W., Kiehl, J., Shields, C., and Zachos, J.: Increased frequency of extreme precipitation events in the North Atlantic during the PETM: Observations and theory, Palaeogeogr. Palaeocl., 568, 110289, https://doi.org/10.1016/j.palaeo.2021.110289, 2021.

Rush, W., Self-Trail, J., Zhang, Y., Sluijs, A., Brinkhuis, H., Zachos, J., Ogg, J. G., and Robinson, M.: Assessing environmental change associated with early Eocene hyperthermals in the Atlantic Coastal Plain, USA, Clim. Past, 19, 1677–1698, https://doi.org/10.5194/cp-19-1677-2023, 2023.

Schaller, M. F. and Fung M. K.: The extraterrestrial impact evidence at the Palaeocene–Eocene boundary and sequence of environmental change on the continental shelf, Philos. T. Roy. Soc. A, 376, 20170081, https://doi.org/10.1098/rsta.2017.0081, 2018.

Schaller, M. F., Fung, M. K., Wright, J. D., Katz, M. E., and Kent, D. V.: Impact ejecta at the Paleocene-Eocene boundary, Science, 354, 225–229, https://doi.org/10.1126/science.aaf5466, 2016.

Schaller, M. F., Turrin, B. D., Fung, M. K., Katz, M. E., and Swisher, C. C.: Initial ^{40}Ar-^{39}Ar ages of the Paleocene-Eocene Boundary impact spherules, Geophys. Res. Lett., 46, 9091–9102, https://doi.org/10.1029/2019GL082473, 2019.

Schmelz, W. J., Miller, K. G., Kopp, R., Mountain, G. S., and Browning, J. V.: Influence of mantle dynamic topographical variations on US mid-Atlantic continental margin estimates of sea-level change, Geophys. Res. Lett., 48, e2020GL090521, https://doi.org/10.1029/2020GL090521, 2021.

Schmelz, W. J, Miller, K. G., Mountain, G. S., Steckler, M. S., Kopp, R. E., and Browning, J. V.: Sensitivity of modeled passive margin stratigraphy to variations in sea level, sediment supply, and subsidence, Basin Res., 36, e12854, https://doi.org/10.1111/bre.12854, 2024.

Schulte, P., Alegret, L., Arenillas I., Arz, J. A., Barton, P. J., Bown, P. R., Bralower, T. J., Christeson, G. L., Claeys, P., Cockell, C. S., Collins, G. S., Deutsch, A., Goldin, T. J., Goto, K., Grajales-Nishimura, J. M., Grieve, R. A. F., Gulick, S. P. S., Johnson, K. R., Kiessling, W., Koeberl, C., Kring, D. A., Macleod, K. G., Matsui, T., Melosh, J., Montanari, A., Morgan, J. V., Neal, C. R., Nichols, D. J., Norris, R. D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W. U., Robin, E., Salge, T., Speijer, R. P., Sweet, A. R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M. T., and Willumsen, P. S.: The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary, Science, 327, 1214–1218, https://doi.org/10.1126/science.1177265, 2010.

Secord, R., Gingerich, P. D., Lohmann, K. C., and MacLeod, K. G.: Continental warming preceding the Palaeocene-Eocene thermal maximum, Nature, 467, 955–958, https://doi.org/10.1038/nature09441, 2010.

Self-Trail, J. M., Hajek, E. A., Edwards, L. E., Robinson, M. M., Bralower, T. J., Sessa, J. A., Kump, L. R., Trampush, S. M., Willard, D. A., Powars, D. S., and Wandless, G. A.: Shallow marine response to global climate change during the Paleocene-Eocene Thermal Maximum, Salisbury Embayment, USA, Paleoceanography, 32, 710–728, https://doi.org/10.1002/2017PA003096, 2017.

Setty, S., Cramwinckel, M. J., van Nes, E. H., van de Leemput, I. A., Dijkstra, H. A., Lourens, L. J., Scheffer, M., and Sluijs, A.: Loss of Earth system resilience during early Eocene transient global warming events, Science Advances, 9, eade5466, https://doi.org/10.1126/sciadv.ade5466, 2023.

Si, W. and Aubry, M.-P.: Vital effects and ecologic adaptation of photosymbiont-bearing planktonic foraminifera during the Paleocene-Eocene Thermal Maximum, implications for paleoclimate, Paleoceanography and Paleoclimatology, 33, 1–14, https://doi.org/10.1002/2017PA003219, 2018.

Sluijs, A., Schouten, S., Pagani, M., Woltering, M., Brinkhuis, H., Sinninghe Damsté, J. S., Dickens, G. R., Huber, M., Reichart, G.-J., Stein, R., Matthiessen, J., Lourens, L. J., Pedentchouk, N., Backman, J., Moran, K., and the Expedition 302 Scientists: Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum, Nature, 441, 610–613, https://doi.org/10.1038/nature04668, 2006.

Sluijs, A., Brinkhuis, H., Schouten, S., Bohaty, S. M., John, C. M., Zachos, J. C., Reichart, G.-J., Sinninghe Damsté, J. S., Crouch, E. M., and Dickens, G. R.: Environmental precursors to rapid light carbon injection at the Palaeocene/Eocene boundary, Nature, 450, 1218–1221, https://doi.org/10.1038/nature06400, 2007.

Sluijs, A., Brinkhuis, H., Crouch, E. M., John, C. M., Handley, L., Munsterman, D., Bohaty, S. M., Zachos, J. C., Reichart, G.-J., Schouten, S., Pancost, R. D., Sinninghe Damsté, J. S., Welters, N. L. D., Lotter, A. F., and Dickens, G. R.: Eustatic variations during the Paleocene-Eocene greenhouse world, Paleoceanography and Paleoclimatology, 23, PA4216, https://doi.org/10.1029/2008PA001615, 2008.

Sluijs, A., Schouten, S., Donders, T. H., Schoon, P. L., Röhl, U., Reichart, G.-J., Sangiorgi, F., Kim, J.-H., Sinninghe Damste, J. S., and Brinkhuis, H.: Warm and wet conditions in the Arctic region during the Eocene Thermal Maximum 2, Nat. Geosci., 11, 777–780, https://doi.org/10.1038/ngeo668, 2009.

Stassen, P., Thomas, E., and Speijer, R. P.: Integrated stratigraphy of the Paleocene-Eocene thermal maximum in the New Jersey Coastal Plain: Toward understanding the effects of global warming in a shelf environment, Paleoceanography, 27, 1–17, https://doi.org/10.1029/2012PA002323, 2012.

Stassen, P., Thomas, E., and Speijer, R. P.: Paleocene–Eocene Thermal Maximum environmental change in the New Jersey Coastal Plain: benthic foraminiferal biotic events, Mar. Micropaleontol., 115, 1–23, https://doi.org/10.1016/j.marmicro.2014.12.001, 2015.

Steckler, M. S., Mountain, G. S., Miller, K. G., and Christie-Blick, N.: Reconstruction of Tertiary progradation and clinoform development on the New Jersey passive margin by 2-D backstripping, Mar. Geol., 154, 399–420, 1999.

Thomas, D. J., Bralower, T. J., and Zachos, J. C.: New evidence for subtropical warming during the late Paleocene thermal maximum: Stable isotopes from Deep Sea Drilling Project Site 527, Walvis Ridge, Paleoceanography, 14, 561–570, 1999.

Thomas, E.: Development of Cenozoic deep-sea benthic foraminiferal faunas in Antarctic waters, Geological Society London Special Publication, 47, 283–296, 1989.

Thomas, E. and Zachos, J. C.: Was the late Paleocene thermal maximum a unique event?, Geologiska Föreningens i Stockholm Förhandlingar (GFF; Transactions of the Geological Society in Stockholm), 122, 169–170, 2000.

Tian, S. Y., Yasuhara, M., Robinson, M. M., and Huang, H.-H. M.: Ostracod eye size: A taxonomy-free indicator of the Paleocene-Eocene Thermal Maximum sea level, Mar. Micropaleontol., 174, 101994, https://doi.org/10.1016/j.marmicro.2021.101994, 2022.

Tierney, J. E., Zhu, J., Li, M., and Kump, L. R.: Spatial patterns of climate change across the Paleocene-Eocene Thermal Maximum, P. Natl. Acad. Sci. USA, 119, e2205326119, https://doi.org/10.1073/pnas.2205326119, 2022.

Tripati, A. K. and Elderfield, H.: Abrupt hydrographic changes in the equatorial Pacific and subtropical Atlantic from foraminiferal Mg/Ca indicate greenhouse origin for the thermal maximum at the Paleocene-Eocene Boundary, Geochem. Geophy. Geosy., 5, Q02006, https://doi.org/10.1029/2003GC000631, 2004.

Vimpere, L., Spangenberg, J., Roige, M., Adatte, T., De Kaenel, E., Fildani, A., Clark, J., Sahoo, S., Bowman, A., Sternai, P., and Castelltort, S.: Carbon isotope and biostratigraphic evidence for an expanded Paleocene–Eocene Thermal Maximum sedimentary record in the deep Gulf of Mexico, Geology, 51, 334–339, https://doi.org/10.1130/G50641.1, 2023.

Wang, H., Kent, D. V., and Jackson, M. J.: Evidence for abundant isolated magnetic nanoparticles at the Paleocene–Eocene boundary, P. Natl. Acad. Sci. USA, 110, 425–430, https://doi.org/10.1073/pnas.1205308110, 2013.

Westerhold, T., Röhl, U., Frederichs, T., Agnini, C., Raffi, I., Zachos, J. C., and Wilkens, R. H.: Astronomical calibration of the Ypresian timescale: implications for seafloor spreading rates and the chaotic behavior of the solar system?, Clim. Past, 13, 1129–1152, https://doi.org/10.5194/cp-13-1129-2017, 2017.

Westerhold, T., Röhl, U., Donner, B., and Zachos, J. C.: Global extent of Early Eocene hyperthermal events: A new Pacific benthic foraminiferal isotope record from Shatsky Rise (ODP Site 1209), Paleoceanography and Paleoclimatology, 33, 626–642, https://doi.org/10.1029/2017PA003306, 2018.

Wing, S. L., Harrington, G. J., Smith, F. A., Bloch, J. I., Boyer, D. M., and Freeman, K. H.: Transient floral change and rapid global warming at the Paleocene-Eocene boundary, Science, 310, 993–996, https://doi.org/10.1126/science.1116913, 2005.

Wright, J. D. and Schaller, M. F.: Evidence for a rapid release of carbon at the Paleocene-Eocene Thermal Maximum, P. Natl. Acad. Sci. USA, 110, 15908–15913, https://doi.org/10.1073/pnas.1309188110, 2013.

Zachos, J. C., Wara, M. W., Bohaty, S. M., Delaney, M. L., Petrizzo, M. R., Brill, A., Bralower, T. J., and Premoli-Silva, I.: A transient rise in tropical sea surface temperature during the Paleocene-Eocene thermal maximum, Science, 302, 1551–1554, https://doi.org/10.1126/science.1090110, 2003.

Zachos, J. C., Röhl, U., Schellenberg, S. A., Sluijs, A., Hodell, D. A., Kelly, D. C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L. J., McCarren, H., and Kroon, D.: Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum, Science, 308, 1611–1615, https://doi.org/10.1126/science.1109004, 2005.

Zachos, J. C., Bohaty, S. M., John, C. M., McCarren, H., Kelly, D. C., and Nielsen, T.: The Palaeocene–Eocene carbon isotope excursion: constraints from individual shell planktonic foraminifer records, Philos. T. Roy. Soc. A, 365, 1829–1842, https://doi.org/10.1098/rsta.2007.2045, 2007.

Zachos, J. C., McCarren, H., Murphy, B., Röhl, U., and Westerhold, T.: Tempo and scale of late Paleocene and early Eocene carbon isotope cycles: Implications for the origin of hyperthermals, Earth Planet. Sc. Lett., 299, 242–249, https://doi.org/10.1016/j.epsl.2010.09.004, 2010.

Zeebe, R. E. and Lourens, L. J.: Solar system chaos and the Paleocene-Eocene boundary age constrained by geology and astronomy, Science, 365, 926–929, https://doi.org/10.1126/science.aax0612, 2019.

Zeebe, R. E., Ridgwell, A., and Zachos, J. C.: Anthropogenic carbon release rate unprecedented during the past 66 million years, Nat. Geosci., 9, 325–329, https://doi.org/10.1038/ngeo2681, 2016.

Zhou, X., Thomas, E., Rickaby, R. E. M., Winguth, A. M. E., and Lu, Z.: I/Ca evidence for upper ocean deoxygenation during the PETM, Paleoceanography, 29, 964–975, https://doi.org/10.1002/2014PA002702, 2014.

Sci. Dril., 33, 67–88, 2024
https://doi.org/10.5194/sd-33-67-2024
© Author(s) 2024. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

CALDERA: a scientific drilling concept to unravel Connections Among Life, geo-Dynamics and Eruptions in a Rifting Arc caldera, Okataina Volcanic Centre, Aotearoa New Zealand

Cécile Massiot[1], Ludmila Adam[2], Eric S. Boyd[3], S. Craig Cary[4,✝], Daniel R. Colman[3], Alysia Cox[5], Ery Hughes[1], Geoff Kilgour[6], Matteo Lelli[7,8], Domenico Liotta[9,7], Karen G. Lloyd[10], Tiipene Marr[11], David D. McNamara[12], Sarah D. Milicich[1], Craig A. Miller[6], Santanu Misra[13], Alexander R. L. Nichols[14], Simona Pierdominici[15], Shane M. Rooyakkers[1], Douglas R. Schmitt[16], Andri Stefansson[17], John Stix[18], Matthew B. Stott[19], Camille Thomas[20], Pilar Villamor[1], Pujun Wang[21], Sadiq J. Zarrouk[22], and the CALDERA workshop participants[+]

[1]GNS Science Te Pū Ao, 1 Fairway Drive, Lower Hutt 5040, Aotearoa New Zealand
[2]School of Environment, University of Auckland, 23 Symonds St. Science Centre, Auckland 1010, Aotearoa New Zealand
[3]Department of Microbiology and Cell Biology, Montana State University, Bozeman, MT 59717, USA
[4]Thermophile Research Unit, Te Aka Mātuatua School of Science, Te Whare Wānanga o Waikato University of Waikato, Kirikiriroa Hamilton 3240, Aotearoa New Zealand
[5]Department of Chemistry & Geochemistry, Montana Technological University, 1300 W. Park St. Butte, MT 59701, USA
[6]GNS Science Te Pū Ao, 114 Karetoto Road, RD4, Taupo 3384, Aotearoa New Zealand
[7]Institute of Geosciences and Earth Resources, National Research Council, Via G. Moruzzi 1, 56124 Pisa, Italy
[8]Istituto Nazionale di Geofisica e Vulcanologia, Via C. Battisti 53, 56125 Pisa, Italy
[9]Dept. of Earth and Geoenviromental Sciences, University Aldo Moro, 70125 Bari, Italy
[10]Microbiology Department, University of Tennessee, Mossman 307, Knoxville, TN, USA
[11]Te Mana o Ngāti Rangitihi, Whakatane, Aotearoa New Zealand
[12]Department of Earth, Ocean and Ecological Sciences, University of Liverpool, 4 Brownlow Street, Liverpool, UK
[13]Department of Earth Sciences, Indian Institute of Technology Kanpur, Uttar Pradesh 208016, India
[14]Te Kura Aronukurangi School of Earth and Environment, Te Whare Wānanga o Waitaha University of Canterbury, Private Bag 4800, Ōtautahi Christchurch 8140, Aotearoa New Zealand
[15]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[16]Earth, Atmospheric, and Planetary Science Department, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907-2051, USA
[17]School of Engineering and Natural Science, University of Iceland, Sæmundargata 2, 102 Reykjavík, Iceland
[18]Department of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, Quebec H3A 0E8, Canada
[19]Te Kura Pūtaiao Koiora School of Biological Sciences, Te Whare Wānanga o Waitaha University of Canterbury, Ōtautahi Christchurch 8140, Aotearoa New Zealand
[20]Institute of Geological Sciences and Oeschger Centre for Climate Research, University of Bern, Baltzerstrasse 1 + 3, 3012 Bern, Switzerland
[21]College of Earth Sciences, Jilin University, Changchun 130061, China
[22]Department of Engineering Sciences, University of Auckland, Private Bag 92019, Ākarana Auckland, Aotearoa New Zealand

✚A full list of authors appears at the end of the paper.
✝deceased, 29 February 2024

Correspondence: Cécile Massiot (c.massiot@gns.cri.nz)

Received: 19 October 2023 – Revised: 18 January 2024 – Accepted: 23 January 2024 – Published: 2 April 2024

Abstract. Silicic caldera volcanoes present major volcanic and seismic hazards but also host dynamic hydrothermal and groundwater systems and a rich but largely unexplored subsurface biosphere. Many of these volcanoes are hosted in rift settings. The intricate connections and feedbacks among magmatism, rifting, hydrothermal processes, and the biosphere in these complex systems remain poorly understood, necessitating subsurface joint observations that are only enabled by scientific drilling. The CALDERA (Connections Among Life, geo-Dynamics and Eruptions in a Rifting Arc caldera) project workshop funded by the International Continental Scientific Drilling Program (ICDP) gathered multi-disciplinary international experts in January 2023 to advance planning of a scientific drilling project within one of these dynamic, rift-hosted calderas, the Okataina Volcanic Centre (OVC), Aotearoa New Zealand.

The OVC's high eruption rate, frequent unrest events and earthquake swarms, location in a densely faulted rapidly extending rift, abundant groundwater–geothermal fluid circulations, and diverse surface hot spring microbiota make it an ideal location for exploring a connected geo-hydro-biosphere via scientific drilling and developing a test bed for novel volcano monitoring approaches. Drilling configurations with at least two boreholes (∼ 200 and ∼ 1000–1500 m deep) were favoured to achieve the multi-disciplinary objectives of the CALDERA project. Decadal monitoring including biosphere activity and composition has the potential to evaluate the response of the hydro-bio system to volcano-tectonic activity. In addition to the OVC caldera-scale datasets already available, site surveys will be conducted to select the best drilling locations.

The CALDERA project at the OVC would provide, for the first time, an understanding of volcanic–tectonic–hydrological–biological connections in a caldera–rift system and a baseline for global comparisons with other volcanoes, rifts, and hydrothermal systems. CALDERA would serve as an unprecedented model system to understand how and how quickly the subsurface biosphere responds to geologic activities. Discoveries will improve assessment of volcanic and seismic hazards, guide the sustainable management and/or conservation of groundwater and geothermal resources and microbial ecosystems, and provide a forum for interweaving mātauranga Māori and Western knowledge systems.

Karakia Whakawātea

Unuhia unuhia
Unuhia te urutapu nui kia wātea
Kia māmā te ngākau, te tinana me te wairua
Koia rā e Rongo, whakairia ake ki runga
Kia tīna! Tīna
Haumi e, Hui e, Tāiki e

Draw away, draw away
Draw away the sacredness and let us be free
Let our hearts, bodies and spirit be unburdened
Oh Rongo suspend this plea up high
And let it be affirmed
Let it be binding, together, all in agreement

As per Māori custom, we start and end this paper (kōrero) with a karakia provided in Te Reo Māori for CALDERA. A karakia is a prayer of respect and thanks to Papatūānuku our Earth mother and sky father Ranginui, as well as to the taiao (environment) that gives us life.

1 Introduction

Caldera–rift settings are ideal for unravelling the connections between volcanic, tectonic, hydrologic, and microbial processes, both between and during episodes of volcanic or tectonic unrest, which are poorly understood (Fig. 1). Caldera volcanoes generate the largest explosive eruptions on Earth by rapidly emptying their magma reservoir in association with earthquakes (Self, 2006). However, the geological drivers of caldera eruptions and earthquakes, their size, their interactions, and their timescales are poorly understood (Hilley et al., 2022). This limits our ability to discern whether signals of activity (e.g. seismicity and ground deformation) are due to volcanic unrest, imminent eruption, or solely tectonic rifting. The combination of a large magmatic heat source and crustal fracturing (e.g. caldera collapse, rift faults, and fracture networks) results in dynamic and complex fluid circulations that need to be better understood to sustainably use

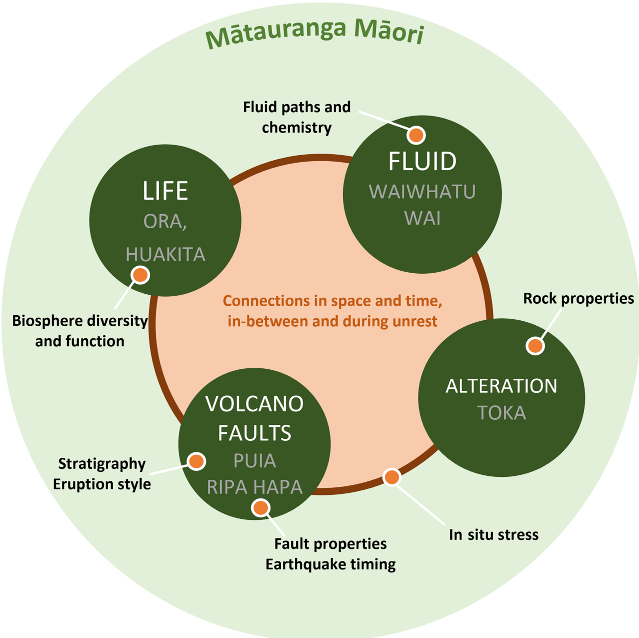


Figure 1. Overview of CALDERA: topics (orange dots) along connected themes (dark-green circles, with a Te Reo Māori language equivalent). Mātauranga Māori (Indigenous knowledge) is intended to be embedded throughout the project.

geothermal and groundwater resources. In hydrothermal settings, little is known about subsurface microbial diversity and how the function and structure of microbial communities react to changes in subsurface processes, either natural (e.g. groundwater recharge, earthquakes, or volcanic activity) or from utilisation of resources (e.g. geothermal or groundwater) (Cluff et al., 2014; Mu and Moreau, 2015). Also unknown are the effects that these changes may have on surface ecosystems (e.g. modulation of greenhouse gases and fluid chemistry).

Multiple feedbacks observed between processes in caldera–rift settings have not been fully reconciled. Faulting and deep basaltic injection, both enhanced by rifting, alter crustal stresses, pore pressures, and magma body overpressures, in some cases triggering voluminous silicic caldera-forming eruptions (Hughes and Mahood, 2011; Allan et al., 2012; Morgavi et al., 2017; Zhan and Gregg, 2019). Fault geometries and activities depend on in situ stress at various temporal and spatial scales, fluid pressure and composition, and rock properties. In turn, rock properties depend on the primary rock type and evolving water–rock interactions. Fluid pathways and compositions are complex due to variable lithologies, hydrothermal alteration, faults, and stress fields, all modulated by volcano-tectonic activity (Wilson and Rowland, 2016). The circulation of mixed hydrothermal and cold meteoric fluids affects the thermal and mechanical states of the crust, which in turn influence the thresholds for both magma chamber failure and fault rupture (Jolie et al., 2016). The deep biosphere composition and activity depend on fluid and rock compositions (Gold, 1992). Conversely, subsurface microorganisms modify rock and fluid properties, likely creating feedback loops traversing deep and surficial processes.

Understanding these connected processes is important for informing strategies to (1) increase resilience to geohazards and (2) adapt to climate change by sustainably conserving and managing geothermal and groundwater resources and their ecosystems, developing biotechnologies, and better understanding elemental cycling for greenhouse gas budgets. Views from local communities, especially Indigenous groups that are closely related to the land (through ancestry, spirituality, use of resources, and wellbeing), are key to developing robust strategies alongside scientific findings.

Multi-disciplinary data arising from scientific drilling have high potential to unravel geo-hydro-bio processes in caldera–rift settings. The Okataina Volcanic Centre (OVC) in the Taupō Volcanic Zone (TVZ), Aotearoa New Zealand, is ideally suited for such an endeavour because it is one of Earth's most active calderas, it interacts with the rapidly extending Taupō Rift, and it hosts active groundwater–geothermal systems and a varied biosphere in hot springs (Fig. 2). Insights made by scientific drilling at the OVC will support understanding of those connected processes worldwide.

This paper summarises the outcomes of an international workshop that advanced planning of the Connections Among Life, geo-Dynamics and Eruptions in a Rifting Arc caldera (CALDERA) scientific drilling concept. Supported by the International Continental Scientific Drilling Program (ICDP), the workshop resulted in an interdisciplinary science plan. In this paper, we start by presenting the OVC and the goal of interweaving mātauranga Māori (Indigenous knowledge) in the project. Then, we articulate CALDERA's research aims and how they address global societal challenges. Finally, we summarise strategies for successfully conducting the project.

1.1 The Okataina Volcanic Centre, Aotearoa New Zealand: a landmark system

The OVC is ideally positioned to address global scientific and societal needs. The OVC is one of two giant active calderas in the TVZ, located within the major active fault system of the Taupō Rift (Cole et al., 2014). The OVC is ranked as Aotearoa New Zealand's highest threat volcano (Miller and Jolly, 2014; Miller et al., 2022a).

The OVC is one of the most frequently active rhyolite volcanic centres on Earth (> 150 km^3 of magma erupted over the last ∼ 50–60 000 years; Nairn, 2002; Wilson et al., 2009), driven by high rates of mantle melting and rapid intra-arc continental rifting (Taupō Rift) (Houghton et al., 1995; Wilson et al., 1995; Nairn, 2002; Cole et al., 2014; Villamor et al., 2017a; Barker et al., 2020). During its known ∼ 625 kyr volcanic history, the OVC has experienced two definite caldera-forming eruptions (Matahina, ∼ 322 ka, and Rotoiti,

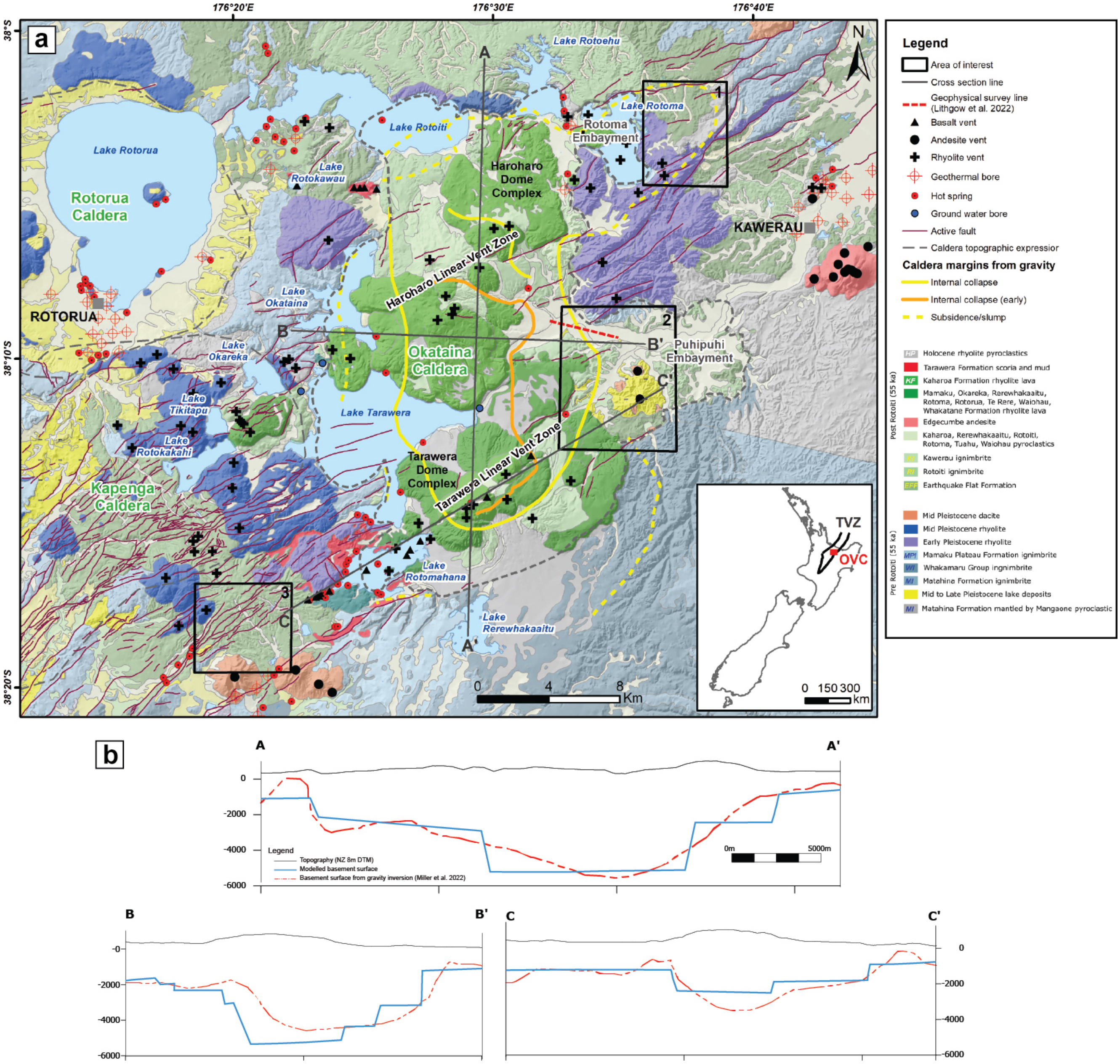


Figure 2. **(a)** Geology of the OVC, location of the active faults (New Zealand Active Faults Database, 2003), structural (as defined from gravity, Miller et al., 2022b) and topographic margins, geothermal and groundwater wells, geophysical survey line (Lithgow et al., 2022; see Fig. 5), and proposed drilling areas. The inset shows the location of the OVC and TVZ in Aotearoa New Zealand. **(b)** Cross sections through the OVC 3-D model showing the basement surface from gravity inversion (Miller et al., 2022b) and geologically modelled (Carson et al., 2022).

50–60 ka). Additional caldera subsidence may have occurred during eruption of the Utu/Quartz-Biotite (∼ 557 ka) and Kawerau (∼ 33 ka) ignimbrites (Nairn, 2002; Cole et al., 2014; Miller et al., 2022b). These major events bracket numerous smaller intra-caldera explosive events and dome-building episodes (e.g. Nairn, 2002). Plinian-scale basalt and rhyolite eruptions have occurred from the same vent systems (Nairn, 2002; Cole et al., 2014), yielding opportunities to sample varied materials from a single location. The latest OVC eruption occurred in 1886 AD at Tarawera Maunga (mountain). Although of a small size for the OVC, the 1886 basaltic eruption cost the lives of ∼ 120 people and heavily impacted local Māori (Rowe et al., 2021). Numerous examples of paleo-earthquakes, in certain cases associated with volcanic eruptions, have been documented on active faults of the Taupō Rift just outside the OVC (Berryman et al., 2022;

Villamor et al., 2022). The OVC region is seismically active and has experienced three seismic swarms in the past 15 years (Benson et al., 2021; Bannister et al., 2022).

The heat from several hydrothermal systems outflowing on the edges of the caldera is inferred to come from the deep magmatic complex in the centre of the caldera (Bertrand et al., 2022). Magmatic fluids interact with abundant freshwater, including groundwater, rivers, lakes, and rainfall of 1.5–2 $\mathrm{m\,yr^{-1}}$ (Giggenbach, 1995; Mazot et al., 2014; Simpson and Bignall, 2016; Hughes et al., 2019; Pearson-Grant et al., 2022; Yang et al., 2023). Diverse microbiota have been identified in the caldera and rift-straddling Waimangu geothermal field (Power et al., 2018, 2024). The absence of geothermal fluid extraction makes the OVC a rare pristine system largely unaltered by human activities.

The OVC has been extensively studied from the surface for decades (Fig. 3, Table S1 in the Supplement). This will enable integration of detailed borehole data in the regional and local contexts to generate transformational research. The record of eruptions since the last caldera-forming event (50–60 ka) is very well documented (e.g. Nairn, 2002) and will allow correlations across boreholes, but small eruptions may still be missing, and the older record is incomplete. The volcano-tectonic paleoseismic record is possibly the best in the world. Natural hazard monitoring data (seismicity, geodetics, and chemistry) collected by the GeoNet programme are publicly available.

1.2 Mātauranga Māori (Indigenous knowledge)

Indigenous knowledge systems are based on intergenerational holistic observation and location-based experience. They are founded on the same principles of hypothesis testing and re-evaluation that underpin contemporary Earth and biological sciences (Lazrus et al., 2022). In Aotearoa New Zealand, the Māori Indigenous Knowledge System is referred to as mātauranga. Mātauranga is defined as the "pursuit and application of knowledge and understanding of te taiao [the environment], following a systematic methodology based on evidence, incorporating culture, values and world views" (Hikuroa, 2017). The holistic approach in mātauranga that includes connections between all aspects of te taiao has great potential to enrich the project outcomes (e.g. Taute et al., 2022).

It is a goal of the CALDERA project to co-design the project with mana whenua (Māori that hold rangatiratanga – sovereignty) and to interweave mātauranga through the lifecycle of the project to ensure the research serves both mana whenua and scientists. Our aim is that mana whenua will be able to contribute to, and directly benefit from, the research findings and their impacts on resilience to hazards, sustainable management of resources and ecosystems, and biotechnology development potential. A bi-cultural outreach programme will particularly benefit rangatahi (the young generation) to support them in becoming next-generation thought leaders.

1.3 Workshop organisation

The CALDERA workshop was held on 24–27 January 2023. Over 40 scientists from 13 countries attended the workshop at Tauranga, Waikato University Campus, Aotearoa New Zealand. An additional nine scientists from four countries participated online. The group covered all disciplines of the project and career stages including students and early-career and senior scientists. Representatives from local government (Bay of Plenty Regional Council, Waikato Regional Council) and drillers (Webster Drilling, Contact Energy Ltd) also contributed to parts of the workshop.

The workshop started with a mihi whakatau (Māori welcome ceremony) by the kaumātua (elder) of the Waikato University campus. Tiipene Marr (Te mana o te Ngāti Rangitihi) introduced the participants to some historical and cultural Māori aspects of the region, followed by a question-and-answer session. Māori aspects were further discussed throughout the workshop, including during the field trip to the Lake Tarawera, Paeroa Fault, and Waimangu geothermal systems.

Prior to the workshop, participants were asked to prioritise the research questions proposed in the ICDP workshop proposal through an online form. This facilitated discussions during the workshop towards addressing recommendations from the ICDP review panel. About two-thirds of the time was dedicated to discussions in breakout groups of single- or cross-discipline and full-group discussions. Opportunities for sharing of knowledge between local Māori and the science team, as well as general education and outreach activities, were discussed. Numerous workshop participants have already conducted outreach activities, including with Indigenous communities, which will facilitate the development of a compelling outreach programme.

2 Global research needs in active caldera–rift systems: CALDERA science plan

2.1 CALDERA aims

The goal of CALDERA is to illuminate the spatiotemporal connections and feedbacks between volcanic, tectonic, hydrological, and biological processes that are especially clear in a caldera–rift setting. The project will advance the grand challenge of resolving the factors underpinning the distribution, abundance, diversity, and activity of deep subsurface biospheres. Associated monitoring data will reveal how and how quickly the system responds to volcanic and tectonic unrest. The project will involve mātauranga Māori for a holistic understanding.

The multi-disciplinary objectives encompass three overarching research topics that will be investigated through sci-

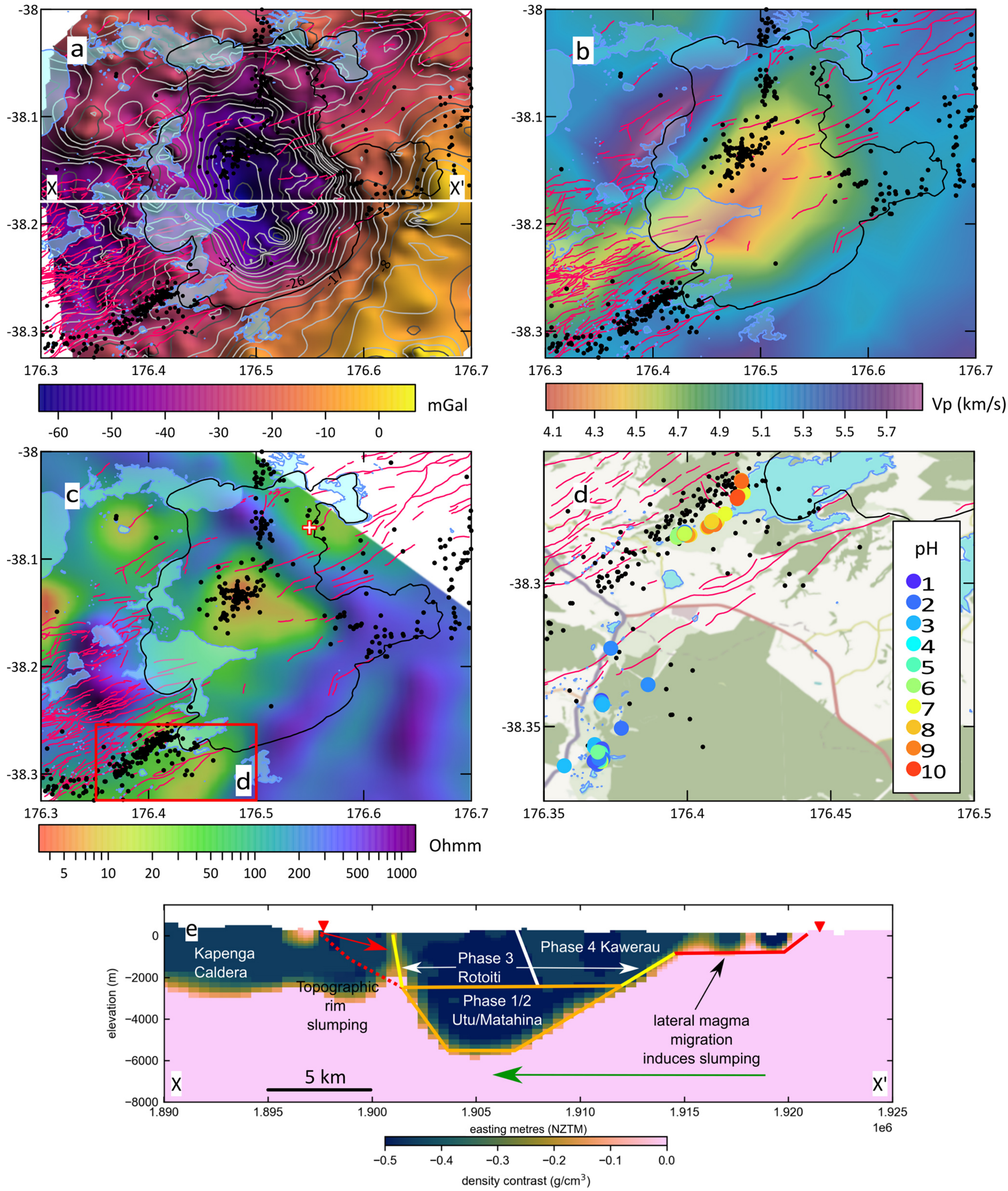


Figure 3. Regional geophysical data around the OVC suggesting a magma reservoir at > 7 km, known active faults (red lines in panels **(a)**–**(d)**), topographical margin of the OVC (black line), and relocated seismicity (black dots). **(a)** Residual gravity anomaly (Miller et al., 2022b). **(b)** P-wave velocity at 3 ± 2 km depth (Bannister et al., 2022). **(c)** Magnetotelluric resistivity model at 4 km (Bertrand et al., 2022). **(d)** pH of some of the hydrothermal features sampled for the fluid chemistry and biosphere during the 1000-spring project in a subset area of the OVC (Power et al., 2018). **(e)** Cross section with inferred structures from gravity (extent in panel **(a)**).

entific drilling to provide a step change in the understanding of

1. the build-up to eruptions of different sizes, including caldera-forming eruptions using the past volcano-tectonic interactions and pre-caldera-forming volcano stratigraphy;

2. how fluid properties and pathways are modulated by volcano-tectonic processes, which influence hydrothermal alteration through time; and how monitoring of fluid property changes contributes to interpreting signals of volcano-tectonic unrest; and

3. how subsurface microorganisms are varied in composition, diversity, and function and sensitively respond to volcano-tectonic activity. The CALDERA project will test whether subsurface microorganisms could serve as early indicators of volcano and/or tectonic events.

Datasets collected during CALDERA will also address a wide range of secondary objectives and contribute to global topics such as volcanic rift basin initiation in active continental margins, rift and volcanic arc evolution, and formation of ore deposits.

2.2 Topic 1: volcanoes, tectonics, and their interactions

Understanding how, when, and why calderas erupt remains among the greatest challenges in Earth sciences because calderas are intrinsically challenging to study, understand, and monitor (Wilson et al., 2021; Sparks et al., 2022). Firstly, deposits from their early eruptions are usually deeply buried or destroyed by later catastrophic eruptions and subsidence, so little is known about the nature, timing, and size of early caldera eruptions or how their magmatic systems mature and evolve towards catastrophic events (Bouvet de Maisonneuve et al., 2021). Secondly, caldera volcanoes are famously restless, but the origins of the unrest are often equivocal, and most unrest episodes do not culminate in eruptions (e.g. Sparks, 2003; Lowenstern et al., 2006; Acocella et al., 2016; Costa, 2021; Illsley-Kemp et al., 2021; Scarpa et al., 2022). Thirdly, caldera behaviour is complex, as it is modulated by interactions between local (volcano-related) stresses and regional stresses and deep magmatic processes that are difficult to disentangle and that may involve complex and non-linear feedbacks (e.g. Bursik et al., 2003; Rowland et al., 2010; Allan et al., 2012; Cabaniss et al., 2018; Muirhead et al., 2022).

Expanding the detailed records of past eruptions is needed to interpret past volcano-tectonic interaction events and help assess tipping points for caldera unrest. Causal relationships between individual earthquakes and volcanic eruptions have been documented over distances that can reach up to hundreds of kilometres but more commonly tens of kilometres (e.g. Linde and Sacks, 1998; Hill et al., 2002; Marzocchi, 2002). The prehistoric record of triggering of volcanic eruptions by large earthquakes and vice versa is world-class at the OVC but still likely incomplete (e.g. Bursik et al., 2003; Berryman et al., 2008, 2022; Muirhead et al., 2022; Villamor et al., 2011, 2022). Historic examples of caldera eruptions are scarce (Hildreth, 1991; Abe, 1992), and the role or significance of large earthquakes within the unrest sequence is difficult to discern in the absence of detailed unrest monitoring.

Crustal structure and magma dynamics are intimately linked at all scales, but how this interaction occurs remains poorly constrained (Walter and Amelung, 2007; Mahony et al., 2011; Villamor et al., 2017a; Oliva et al., 2019). The weakening of the crust by a magma reservoir influences the location, style, and rates of activity of faults in colder areas of the adjacent rift (van Wyk de Vries and Merle, 1996; Lahitte et al., 2003; Ellis et al., 2014; Villamor et al., 2017a, 2022), yet modelling relies on incomplete data (Corti, 2012). Fault rupture occurs due to increased stresses and/or fluid pressure on the fault plane (Byerlee and Savage, 1992). While stresses from magma dynamics and fault ruptures have been quantified for decades (Stein, 1999; Ruz-Ginouves et al., 2021), changes in fluid pressure during these processes are difficult to quantify without direct measurements.

Accessing the subsurface of caldera–rift systems via scientific drilling is needed to address these challenges by (1) sampling thin or deeply buried early eruption deposits to complete eruption histories, understand volcanic evolution prior to a large caldera-forming event, and infer influences on rift evolution; (2) revealing the internal rock composition, structure, and properties of fault zones (e.g. strength, permeability); (3) measuring in situ stresses; and (4) monitoring strain, seismicity, and fluid properties to guide interpretation of unrest. Downhole monitoring of faults near the caldera, together with regional volcano-tectonic monitoring and detailed understanding of past events, is needed to understand the faults' changing conditions caused by volcanic unrest, rifting, or both. These will contribute to assessing whether unrest may lead to an eruption, a large earthquake, or both.

2.3 Topic 2: fluid properties, pathways, and water–rock interactions

2.3.1 Hydrology, fluid properties, and structural permeability

The origin and chemistry of fluids in magmatic–hydrothermal systems are complex. Deep fluids at lithostatic pressure near the magmatic heat source (superheated or supercritical fluid, saline or hypersaline brines rich in volatiles) mix with meteoric waters to yield fluids in the liquid or vapour phase, circulating at shallow levels at or below hydrostatic pressure. Conceptual models of hydrothermal systems suggest that the low-permeability zone around the brittle–ductile transition is episodically penetrated by magmatic volatiles in response to stress and strain changes (e.g. Hayba and Ingebritsen, 1997; Fournier, 1999; Scott et al., 2015). Validating these models and investigating the continuous interplay among magmatic and geothermal fluids and freshwater require monitoring of the chemistry of subsurface hydrothermal fluids that reflect magmatic inputs in a pristine system not modified by geothermal energy developments.

Fluid flow paths in caldera–rift systems are strongly controlled by fracture networks (e.g. Arnórsson, 1995; Norini et al., 2019; Rowland and Simmons, 2012) and typically difficult to evaluate. Fracture networks are determined by competing factors that are insufficiently understood individually and in conjunction: (1) spatiotemporal connections between rift and caldera fault systems among regional fractures (Acocella, 2014; Villamor et al., 2017a); (2) fracture kinematics with respect to crustal stress states (Sibson, 2000) and connectivity among fractures (Sanderson and Nixon, 2015); (3) fluid–rock interaction processes that vary with fluid pressure and chemistry (McNamara et al., 2016; Zucchi et al., 2017; Uno et al., 2022); (4) in situ stress variations arising from fluid-pressure changes (sealing during progressive magma cooling) and gravitational collapses (Somr et al., 2023); and (5) repeated volcanic and tectonic events that maintain fluid circulations from deep to shallow (Shapiro et al., 2017). Volcanic and lake sediments also contribute to a heterogeneous permeability within calderas that is difficult to assess from the surface. Ground deformation caused by volcanic and rifting processes also influences the fracture network connectivity and fluid conditions (Battaglia et al., 2006; Gottsmann et al., 2007; Hutnak et al., 2009).

Only co-located measurements of rock and fracture properties, in situ stress, and fluid compositions and pathways can clarify connections among the factors that drive fault activity and permeability. Caldera–rift systems are ideal for exploring these unresolved processes because they host intense fluid circulations driven by large heat sources and with faults that are often reactivated. Drilling is required to (1) identify flow paths and quantify the mixing between meteoric recharge (including multi-layer aquifers) and deep magmatic–hydrothermal fluids, including in response to volcanic unrest or fault activity; (2) access depths where fluids are less or not affected by surface water bodies and shallow groundwater; and (3) obtain cores to characterise the fracture network and its evolution through past volcano-tectonic events. Downhole monitoring is the best way to identify changes in fluid composition in response to volcanic or tectonic activity. These subsurface data are needed to parametrise hydro-mechanical models, with implications for biosphere studies.

2.3.2 Volcanic rock properties and evolution of hydrothermal alteration

Volcanic rock properties underpin the understanding of volcanic and hydrothermal systems. These fundamental datasets and concepts are needed to interpret geophysical surveys and calibrate models of deformation (faulting, caldera collapse), hydrology, and how mineral composition affects the deep biosphere. In turn, these models are needed to interpret signals of tectonic and volcanic activity. Hydrothermal alteration types and kinematics are driven by the combination of (1) host rock mineralogy; (2) subsurface fluid chemistry; (3) fluid pathways; and (4) pressure and temperature conditions. The interpretation of the evolution of hydrothermal alteration and how it changes volcanic rock properties is insufficiently constrained globally due to the scarcity of multi-scale borehole data.

The evolution of hydrothermal alteration has contrasting and variable effects on volcanic rock properties. Argillic alteration can alternately increase porosity and weaken rocks (Wyering et al., 2014) or decrease permeability and strengthen rocks (Mordensky et al., 2018; Nicolas et al., 2020). Acid–sulfate alteration on andesitic rocks can increase (Kennedy et al., 2020; Kanakiya et al., 2021a) or decrease (Heap et al., 2019) porosity and permeability. The original rock microstructure, especially porosity and permeability, influences hydrothermal alteration (Mordensky et al., 2019; Heap and Violay, 2021), but the original volcanic rock properties have been characterised for only a few lithologies sampled at different stratigraphic intervals or localities (Pola et al., 2014; Mordensky et al., 2019; Kanakiya et al., 2021a). Laboratory experimental studies have primarily focused on the influence of hydrothermal alteration upon fluid pathway evolution (Pola et al., 2014; Wyering et al., 2014), rheology and strength (Heap and Violay, 2021), elastic wave velocities (Kanakiya et al., 2021a), resistivity (Komori et al., 2013), and magnetisation (Kanakiya et al., 2021b). Extrapolating to the field scale to understand how hydrothermal alteration influences deformation and geophysical signatures requires in situ microscale-to-macroscale data.

Scientific drilling is the only way to jointly provide cores, geophysical logs, subsurface fluid samples, and in situ stress measurements that are necessary to identify (1) key geochemical–mechanical processes that govern the evolution of volcanic rock properties and (2) the thermochemical–biological processes that facilitate subsurface mineral growth and dissolution. The varied rock textures and intense fluid circulations that likely changed through time make caldera–rift systems excellent localities to understand interactions between fluids (magmatic and meteoric) and different lithologies, both within and outside fault zones.

2.4 Topic 3: deep biosphere diversity, function, and geobiological interactions

Very little is known of the extent of deep subsurface biospheres, how they are sustained, how they respond to geologic processes (e.g. seismic or magmatic activity), and how they alter fluid or rock properties. This is due in large part to logistical difficulties in accessing suitable environments or samples for study and, more importantly, in coordinating sampling events with geologic events (e.g. earthquakes). Fluid build-up in volcanic environments can be released through seismic activity, with localised subsurface effects occurring in both local and linked, but distinct, geothermal systems (Payne et al., 2019). Further, low-magnitude seismic events may increase the connectivity of fluids in the subsurface, expose fresh mineral surfaces for water–rock interactions, and release trapped substrates or even generate new substrates (e.g. methane, hydrogen, hydrogen peroxide, or sulfate) capable of supporting microbial metabolisms (Telling et al., 2015; Stone et al., 2022). Finally, extensive fracturing and faults in caldera–rift systems permit fluid flow that can further concentrate volcanically derived volatiles (e.g. CO_2 or H_2S) (Lowenstern et al., 2015) that can support subsurface microbiomes.

Collectively, these observations offer a compelling argument for seismic and volcanic activity directly supporting subsurface microbial activity, although the characteristics, magnitudes, and timescales of such responses are only beginning to be studied (e.g. Payne et al., 2019). There is therefore a critical need to develop new approaches, techniques, and infrastructure to assess responses of subsurface biospheres to geologic processes, particularly in volcanically and seismically active regions. As of now, they are mainly investigated through their surface manifestations (hot springs), which indicate that subsurface microbial communities are acutely responsive and sensitive to spatial changes in the physicochemical composition of aquifers sourcing the springs (Colman et al., 2021; Fullerton et al., 2021; Power et al., 2023). Collectively, these studies are strong indicators that subsurface litho-autotrophic microbial ecosystems (SliMEs) in hydrothermal systems would similarly be responsive to input of geogenic electron donors or acceptors, regardless of the process involved (e.g. increased connectivity of aquifers, release of fluid inclusions, or increased water–rock interactions).

In addition to the influences of geophysical, geochemical, and hydrological processes on subsurface biospheres, microbial activities also exert feedback that can alter subsurface fluid, rock, and mineral properties. However, little is known of the extent of microbial influences on these properties, and particularly at temperatures greater than 40 °C (Magnabosco et al., 2018). Indirect evidence from surface features suggests that subsurface microbial communities alter hydrothermal fluid compositions through their metabolism of inorganic substrates, the acidification of hydrothermal waters (Mosser et al., 1973; Nordstrom et al., 2005; Colman et al., 2022), consumption of gases (e.g. H_2 and CH_4) (Wankel et al., 2011), alteration of minerals (Casar et al., 2020; Templeton and Caro, 2023), and precipitation of minerals (e.g. calcite) (Barry et al., 2019). The extent of these activities, their potential to significantly alter mineral assemblages, and their ability to predict geologic events remain poorly understood.

Scientific drilling is the only way to coordinate sampling subsurface fluids and the SliMEs they support to address the critical need to identify the temporal nature and indicators of functional responses with volcanic and tectonic events common to caldera systems. Borehole monitoring provides the required natural observatory to explore the feedbacks between microbial activity, the geosphere, and the hydrosphere. The diversity of magmatic and hydrothermal processes at the OVC implies a similar diversity of such ecosystems, both spatially and temporally, including in a borehole connected to fluids at varied temperature and composition.

2.5 Summary: scientific drilling in caldera–rift settings can best address global knowledge gaps

Calderas located in rifts are ideal natural laboratories for addressing CALDERA's research topics and global knowledge gaps. In caldera–rift systems, volcanic eruptions and earthquakes occur frequently, both separately and together, making them ideal environments for identifying and evaluating precursors of eruptions of varied sizes and styles. Large heat sources and faults result in dynamic fluid circulations that support a diverse biosphere.

Only scientific drilling can provide the subsurface, continuous, multi-disciplinary, and high-resolution records insulated from surface processes and furthermore provide later access for decadal monitoring. While there are thousands of boreholes for commercial geothermal energy use in terrestrial calderas, access to data from these boreholes is commonly limited by both technical constraints imposed by high temperatures (> 150 °C) and confidentiality. Groundwater wells are shallow (< 100 m) and often lack cores. Hot springs are often unsuitable analogues to the deep hydrothermal fluids and biosphere because they are subject to extensive mixing with near-surface fluids and are infused by oxidised atmospheric gases that exert strong influences on hot spring microbiology (Colman et al., 2019). Ocean scientific drillings in hydrothermal settings have investigated aspects such as seawater–rock interactions (Bach et al., 2003), but they remain sparse, cannot be directly transferred to low-salinity systems, and rarely involve in situ stress measurements or monitoring. The CALDERA programme is ideally positioned to address multiple knowledge gaps.

2.6 Lessons arising from CALDERA will be applicable globally

The CALDERA project proposes, for the first time, to develop understanding of the complete volcanic–tectonic–hydrological–biological system in a caldera–rift system. Mutually enriching relationships with communities, including Indigenous Māori, will advance good practice guidelines for such projects globally.

The new multi-disciplinary datasets and models developed at the OVC will unlock understanding at other volcanoes, calderas, rifts, and hydrothermal systems. The precursors to earthquakes and volcanic eruptions identified at the OVC will be transferable to caldera systems globally. Clarification of feedbacks between magmatic or meteoric fluid flow and faults will be generally applicable to improving understanding of crustal processes and assessing geohazards and the sustainable use of resources. Findings on volcanic rock properties and evolutionary alteration processes will significantly grow the global dataset. The OVC will serve as an unprecedented model system to quantify the influence of seismicity and volcanic unrest on the activity and function of microbial communities, resulting in a comprehensive understanding of global subsurface biosphere activities and responsiveness to associated environmental drivers.

By targeting moderate temperatures (40–150 °C) and groundwater–hydrothermal systems, CALDERA is complementary to other scientific drilling projects targeting deeper supercritical and magma systems (e.g. Newberry – NDDP, USA; Krafla – KMT and IDDP, Iceland; Japan – JBBP). With the clear expression of the Taupō Rift, CALDERA is complementary to the ICDP/IODP project at the partly submerged and weakly rifted Campi Flegrei caldera (Italy, De Natale et al., 2016). IODP expeditions to Brothers Volcano in the Kermadec Arc offshore New Zealand (Expedition 376, de Ronde et al., 2019) and to the Hellenic Arc Volcanic Field (Expedition 398, Druitt et al., 2022) will provide onshore–offshore comparisons of arc volcanisms, caldera processes, and reactions of ecosystems to volcanic eruptions.

3 Societal relevance

In addition to increased scientific understanding of Earth processes occurring in rifted calderas, CALDERA will significantly contribute to improving societal goals.

3.1 Geohazards: increase resilience to volcanic and seismic hazards

A major caldera-forming eruption (volcanic explosivity index VEI > 6–7) would have severe human, economic, and climatic repercussions globally (Self, 2006). While smaller eruptions are less devastating than large ones, their higher frequency may pose the most significant risks to local and regional communities and can lead to national-scale social and economic disruption (e.g. the 1886 Tarawera eruption at the OVC; Rowe et al., 2021). Earthquakes that occur during volcanic eruptions (sometimes $M > 6.0$; Villamor et al., 2011) are difficult to include in seismic hazard models. Caldera unrest generates high interest and concern among local communities (e.g. during the 2022 Taupō caldera unrest, Aotearoa New Zealand). A global analysis by the European Science Foundation calculated the benefits of understanding and monitoring supervolcanoes at USD 0.5–3.5 billion per annum (Plag et al., 2015).

Converting scientific knowledge into tailored hazard planning advice allows decision-makers to better anticipate and assess the volcanic and seismic hazards through optimised monitoring and education programmes, leading to improved community resilience. This outcome is aligned with ICDP Theme 2 *Geohazards* and addresses key targets of the UNDRR – Sendai framework For Disaster Risk Reduction 2015–2030.

3.2 Georesources: foster the sustainable use and protection of hydrothermal and groundwater resources

Large populations live near calderas and their geothermal resources (e.g. in Kenya, Mexico, and Japan; Lund et al., 2022). Communities also need access to freshwater for drinking, farming, and recreational uses. Technologies to extract metals (e.g. Au, Ag, or Li) and silica (Simmons et al., 2016) and to store CO_2 are rapidly emerging in geothermal operations. Although geothermal energy is already produced from calderas worldwide, new or expanded developments are limited by high economic risk due to limitations in (1) mapping heat sources, fluid pathways and fluid chemistry as well as understanding their spatiotemporal variations (Jolie et al., 2021); (2) quantifying meteoric water recharge; and (3) understanding links between subsurface and surface water features that are important culturally, spiritually (especially for Indigenous communities), economically (e.g. bathing, cooking, and tourism), and generally for wellbeing.

Fostering the sustainable management, protection, and access to hydrothermal and groundwater resources aligns with ICDP Theme 3 *Georesources*, contributes to the UNESCO sustainable development goals, and supports reduction of CO_2 emissions under the Paris Agreement.

3.3 Deep biosphere

Microorganisms and their metabolic activities drive Earth's biogeochemical cycles that support and sustain global ecosystem health (Falkowski et al., 2008). Geological processes in continental hydrothermal systems (fluid circulation inducing physicochemical variations, mineral precipitation or dissolution) are known to drive microbial community composition and activity (Fullerton et al., 2021), but less is known about the responses of microbial communities to rapid geological events like those in caldera–rift settings. The extent, rate, and sensitivity of these responses remain to be determined, constituting the next frontier of environmental microbiology studies.

Understanding how and when such substrates are available to subsurface microbiomes is central to understanding their role in Earth's biogeochemical cycles and generally the development of Earth's hydrosphere–atmosphere–biosphere system (ICDP Theme 1, *Geodynamic processes*). Moreover, a better-resolved understanding of subsurface biosphere–geosphere interactions in active volcanic regions would enable the development of microbial indicators of volcanic unrest (ICDP Theme 2, *Geohazards*). Finally, studies of little-understood subsurface microbiomes would improve strategies for conserving and managing these critical microbial ecosystems, improve estimates of greenhouse gas budgets, promote new biotechnological developments including renewable energy production and greenhouse gas storage (ICDP Theme 3, *Georesources*), and inform the search for life in rocky exoplanet subsurface settings.

4 Proposed strategies for scientific drilling

4.1 Drilling plan

The CALDERA project aims to collect cores, geophysical logs, in situ stress measurements, and downhole fluid samples and to provide long-term (ca. 10-year) borehole access for monitoring. Borehole data will be interpreted in the context of local- and regional-scale surface datasets. To achieve the scientific and societal objectives, drilling must

- be located in a zone of active seismicity to test the fluid and biosphere response to nearby earthquakes;
- intersect volcanic products pre-dating the last caldera-forming eruption (Rotoiti Ignimbrite, ∼55–60 ka) that are likely missing or poorly represented from surface records;
- collect cores, downhole logs, and fluid samples across an active permeable fault to reveal fault zone textures as well as mechanical and hydraulic properties;
- measure the downhole pressure and temperature as boreholes warm up to locate all permeable intervals and measure the well injectivity and productivity;
- collect fluid samples to quantify the mixing between meteoric recharge and deep magmatic–hydrothermal fluids, sample the subsurface biosphere, and evaluate their effects on mineral alterations;
- be located near hot springs to establish potential hydraulic and biosphere connections between the subsurface and surface, including in response to seismic or volcanic activity;
- intersect the water table at shallow depth and high-permeability rocks to allow for natural fluid recharge within a few days, i.e. a timescale relevant for measuring a microbial response;
- obtain cores from rocks not too hydrothermally altered in at least some borehole sections to provide characteristics of eruptions and a complete chronostratigraphy (usually difficult for hydrothermally altered samples);
- collect cores and geophysical logs across a variety of lithologies to maximise learning about volcanic rock properties and fluid–rock interactions together with their effects on fault properties, fluid circulations and chemistry, and biosphere composition and activity;
- reach 1000–1500 m depth to limit near-surface effects on in situ stress measurements (topographic effects), fluids, rock properties, and fault splays; and
- have at least parts of the boreholes at <40–$120\,°C$, where the biosphere is readily detectable and known to be active, and overall $<150\,°C$ to be able to rely on conventional downhole tools: a gentle temperature gradient would be ideal for evaluating changes in biosphere, fluid, and rock properties as a function of temperature.

The precise drilling location, configuration, and activities will be decided based on these scientific requirements together with landowners, local Māori, and regulatory agencies. Lake beds and wahi tapu (sacred land) areas are excluded due to cultural sensitivity.

Social license will be carefully assessed during site surveys, drilling planning, and drilling and monitoring through community engagements, particularly regarding mātauranga and values. The CALDERA project does not seek to modify the volcanic environment, suppress natural processes, or interact directly with magma, which will facilitate gaining of community support. The scientific boreholes will be used for monitoring rather than the continuous fluid extraction or injection conducted in the numerous geothermal and groundwater boreholes in the TVZ. Public risk perception of a potential unforecasted volcanic or seismic event triggered by drilling (Cassidy et al., 2023) will be mitigated in several ways. First, extensive social engagement will communicate that the project aims to monitor rather than modify the volcano. Early communication about the volcano's behaviour prior to drilling, including potential periods of unrest (seismic swarms), will lower the likelihood that a period of unrest may be perceived as caused by drilling. Second, deliberately targeting the margins and outside parts of the caldera and staying away from magma (spatially and with depth) will decrease potential safety and ethical concerns. Third, the project will follow current regulatory processes that require community support, low environmental impact, and safety assessments. Obtaining regulatory permits will be facilitated by the ongoing discussions with regional councils and their attendance at the workshop. Hundreds of geothermal, mineral, and water drillings have been conducted in the TVZ since the 1950s, including at the nearby Kawerau and Rotorua geothermal fields. None of these wells has intersected magma and, due to the TVZ being a naturally seismic area, induced microseismicity has not caused public concern (Sherburn et al., 2015a, b). Finally, an evaluation and risk mitigation plan will be conducted prior to drilling, using experience gained from drilling TVZ geothermal fields, and in other ICDP projects (e.g. the DFDP-2 project targeting the Alpine Fault, Chamberlain et al., 2017; in preparation for magma drilling of the Krafla Magma Testbed, Ilic et al., 2021). Those plans will be supported by decades of experience in volcano and seismic monitoring and community engagement in the TVZ.

Three potential drilling areas were delineated (Fig. 2). They are located outside the caldera structural margin, so that stratigraphy is not dominated by thick intracaldera deposits of large caldera-forming eruptions that can exceed 1 km thickness (e.g. Rosenberg et al., 2020). Two locations (labelled "1" and "3" in Fig. 2) contain mapped active faults where past volcano-tectonic activity is documented (Berryman et al., 2022; Villamor et al., 2022), currently experience frequent seismic activity (Bannister et al., 2022), and have nearby hot springs. Products pre-dating the last caldera-forming eruption (55–60 ka) are shallow in Area 3, as abandoned geothermal wells to the south of the area intersected the Waiotapu Ignimbrite (0.71 ± 0.06 Ma) at 236 m (Grindley, 1963). In Area 1, the top of the Rotoiti Ignimbrite crops out in eroded valleys (Villamor et al., 2022). Area 2 (Puhipuhi Basin) contains a structural caldera margin clearly imaged by gravity and electric surveys (Lithgow et al., 2022; Miller et al., 2022b). Thick (potentially > 100 m) recent (post-Rotoiti Ignimbrite) pumice deposits prohibit paleoseismic studies. This area experienced a deep seismic swarm in 2019 (Benson et al., 2021). The Puhipuhi Basin is hydrothermally altered and contains possible mineralisation. The biosphere has been studied in multiple springs at Waimangu near Area 3 (Power et al., 2018).

Achieving the multi-disciplinary objectives in this complex system requires at least two boreholes. Excellent existing tephra records provide multiple marker layers for stratigraphic correlations. At least one borehole should be inclined (i.e. deviated from the vertical) to intersect the entirety of a fault and its damage zone, as fault dip angles are generally high in the TVZ (60–80°; Villamor et al., 2017b; McNamara et al., 2019). A shallow borehole (about 200 m depth, temperature < 120 °C) would primarily focus on biosphere and hydrology aspects, especially connections between the subsurface and surface. A deep borehole (1000–1500 m depth) would primarily focus on stratigraphy, tectonics, in situ stress, rock properties, and hydrothermal fluids, including monitoring of volcano-tectonic activity and changes in deep fluids. Biosphere studies would also be conducted in this deep borehole if temperatures permit. Site characterisation will ensure that stratigraphic and structural targets are reached, but estimating the temperature profile prior to drilling will be difficult. Indeed, convection dominates in the TVZ, and lateral or downward-directed groundwater flows commonly interact with ascending hydrothermal fluids.

Several drilling configurations were discussed during the workshop (Table 1, Fig. 4). Drilling a deep borehole and a shallow borehole in the same area increases the chances of addressing the multi-disciplinary objectives and provides opportunities for cross-borehole studies (e.g. tracer tests and variations in rock properties, fluids, and the biosphere) but restricts the exploration of the complex caldera system to a single area. If drilled in the same area, drilling a shallow borehole first (possibly as part of site characterisation) derisks the deep, more expensive borehole. Drilling pairs of boreholes in two areas offers the best coverage of the OVC and maximises research outcomes but is more expensive. The final drilling configuration will be determined following detailed site surveys of the three target locations.

The modest temperature and depth targets facilitate the use of conventional drilling materials and a large suite of downhole logging measurements, downhole fluid sampling, installation of optic fibres for monitoring (e.g. distributed acoustic and temperature sensing – DAS, DTS), and other long-term observational instruments (e.g. seismometer, tiltmeter). Extended leak-off tests will be run at casing points for in situ stress measurements. Packers for permeability and in situ stress measurements will be deployed if the temperature is within operating limits. An online gas monitoring system (OLGA, Erzinger et al., 2006) during drilling and transient well tests will also be used.

Biosphere studies will focus on post-drilling downhole fluid sampling using the Kinetically Activated Subsurface Microbial Sampler (KASMS). The KASMS is designed to autonomously collect and preserve up to six sets of fluid samples for use in quantifying microbial cell number and activity, to conduct molecular analyses (i.e. to identify shifts in the taxonomic and functional composition and the diversity of microbial communities), and to conduct geochemical analyses. The KASMS can be triggered by a seismic tremor above a set minimum magnitude or otherwise triggered remotely on demand, which then initiates a series of sample collection processes at user-defined time intervals (Freifeld et al., 2005). The KASMS will be essential for evaluating the response of SliMEs to nearby earthquakes in hydrothermal systems. Problematic microbial contamination from drilling will be minimised by sampling only post-drilling. Therefore, UV filtering of drilling fluids will not be needed, which substantially simplifies drilling planning and reduces costs. The time needed for water-based drilling fluids to dissipate after drilling will need to be evaluated to avoid contamination.

4.2 Site characterisation

The extensive collection of the existing datasets at the OVC (see the Supplement) will (1) facilitate drill-site selection and (2) enable borehole samples to be placed in a regional-scale context. Based on gravity inversions, the depth of the basement top is estimated to be between 1000 and 2000 m depth in the three areas (Stagpoole et al., 2021; Miller et al., 2022b). Faults are well mapped onto a surface using lidar combined with paleoseismic trenches in Areas 1 and 3 (two and seven trenches, respectively, accompanied by ground-penetrating radar profiles across fault strands) (Berryman et al., 2008, 2022; Villamor et al., 2022). Magnetotelluric surveys at 2 km spacing cover Area 2 (Bertrand et al., 2022) and are scheduled to be acquired in Area 3 in the next few years. Airborne magnetic data cover all the areas.

Table 1. Potential drilling configurations (illustrated in Fig. 4). Shallow means ∼ 200 m depth, and deep means ∼ 10 000–1500 m depth.

Drilling strategy	Timing	Advantages	Drawbacks
Optional preparatory drilling: one shallow vertical borehole (Option a in Fig. 4)	At least 1 year before further drilling	– Low cost, low temperature – Quantify the time for drilling fluids to exit the borehole. – Assess near-surface drilling hazards. – Provide some temperature information. – Provide a shallow direct portal for monitoring of fluids, pressures, and geophysical responses. – Provide a trial run for the team.	– Limited benefits for volcanology, rock properties, and in situ stress studies – Extra cost of rig mobilisation
One deep and one shallow borehole in a single area		– Different objectives for each hole increase the chances of successful acquisition of all the datasets (e.g. due to temperature limitations). – Assessment of lateral heterogeneity – Opportunities for cross-borehole studies (lateral fluid and pressure communication; biosphere, seismic, and electrical structure)	Only one area explored
	Shallow then deep ("IODP approach"; Option b in Fig. 4)	– Some indications of the temperature gradient for planning the deep hole – A shallow hole provides an indicator of potential deeper hazards.	Higher risk that a shallow hole does not intersect a fault
	Deep then shallow (Option c in Fig. 4)	Certainty that the temperature profile in the shallow borehole and fault intersection fits biosphere requirements	Higher risk for the deep (more expensive) hole
One shallow in one area, one deep in another area		Wider coverage of the system than a single area	Higher risks of missing targets and too high temperature
Two holes (shallow then deep, Option b in Fig. 4) in two different areas		Highest spatial coverage	Higher costs

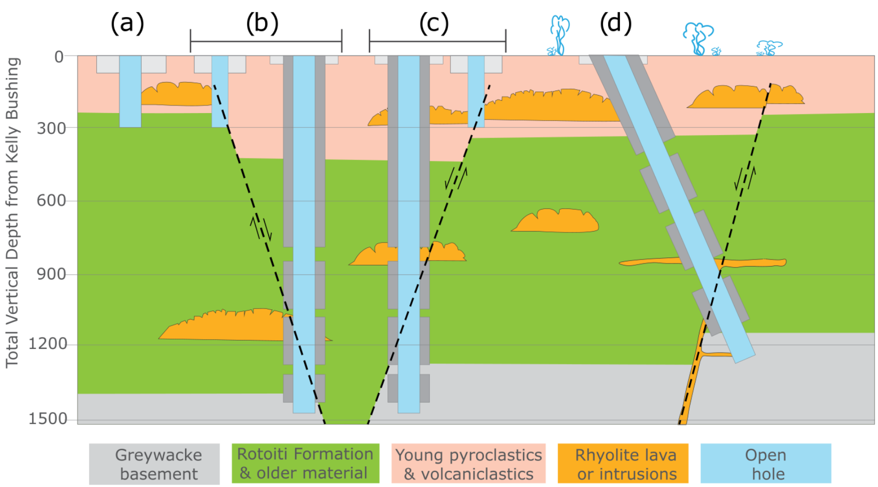


Figure 4. Potential drilling scenarios (see Table 1). The geology is speculative, with the Rotoiti Formation (last caldera-forming eruption at ∼ 55–60 ka) and older deposits thickening towards the centre of the caldera, i.e. not necessarily with constant thickness across the faults. Lavas and especially intrusions (dikes and sills) are difficult to image prior to drilling. The cased hole sections (light and dark grey) represent near-surface "conductor" casing and deeper cemented borehole casing. Open-hole or perforated sections exist where no casing is shown. **(a)** Shallow preliminary test hole to ∼ 200 m depth. **(b)** Shallow then deep borehole. **(c)** Deep then shallow borehole. Deep holes in panels **(b)** and **(c)** could be either vertical or inclined to optimise steep fault intersection. An example of an inclined borehole is presented in panel **(d)**.

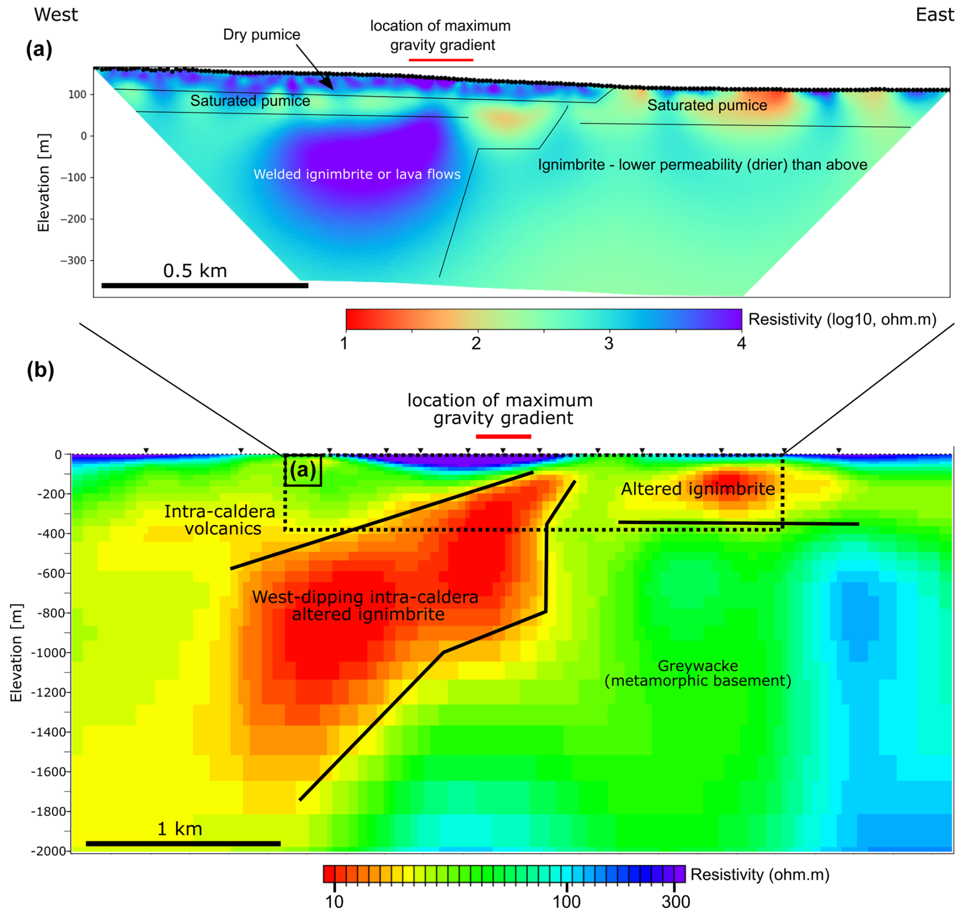


Figure 5. Geophysical imaging of the eastern OVC caldera margin (location in Fig. 1). **(a)** Electrical resistivity tomography. **(b)** Magnetotelluric. The dotted square shows the extent of panel **(a)**. The red bar indicates the maximum gravity gradient. The colour maps are optimised for the data ranges of each survey. After Lithgow et al. (2022).

An electrical resistivity tomography (ERT) line (2 km long, 10 m electrode spacing) and a 2-D magnetotelluric profile (4 km long, 13 sites) (Lithgow et al., 2022) were surveyed over the OVC's steepest gravity gradient in Area 2. Despite a lack of topographical relief and surface fault expression caused by infill by recent pumice material, the survey clearly imaged the eastern margin of the OVC (Fig. 5).

To further refine the drilling sites, we will undertake multiple geophysical surveys. We will deploy a dense nodal seismic array to image faults in the uppermost 1 km and potentially stratigraphic markers. Closely spaced gravity measurements will refine the depth to basement and basement fault offsets, especially in Areas 1 and 3, where the existing data are sparse. Drone magnetic surveys in areas with poorer airborne coverage will improve hydrothermal alteration mapping. A joint ERT and magnetotelluric profile in Areas 1 and 3 will refine fault location and identify possible hot (or saline) fluid or clay alteration. Self potential and CO_2 soil gas surveys will help determine groundwater flow and connections to deep magmatic sources. A seismic reflection experiment with a 2-D profile of transit time tomography will be considered to locate faults, although the highly scattering subsurface produces poor imaging in the TVZ. Shallow fault imaging may also include additional paleoseismic trenching, ground-penetrating radar, and a shear wave land streamer system (Polom et al., 2016).

Shallow drill cuttings from the Kawerau Geothermal Field will be revisited to identify the base of the Rotoiti Ignimbrite. Spring temperature, chemistry, and isotopes in the OVC region will be compiled. If necessary, additional fluid sampling will be conducted for fluid and biosphere studies, based on geographical distribution and altitude, fault alignments, and surface geology, to provide a framework for interpreting downhole fluids and the biosphere.

4.3 Data and sample management plan

The OVC lies within the rohe (territories) of multiple iwi. As recognised by the 1840 Te Tiriti o Waitangi (Treaty of Waitangi) and the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), this accords mana whenua authority over data and/or samples (geological, water, biological) collected from the OVC. Reflecting this, the data and sample management plan applied in this research programme will be guided by the principles of Indigenous data governance (Kukutai et al., 2023) and will be co-designed with mana whenua (e.g. as in Power et al., 2024). In parallel, the data and sample management plan will also need to reflect the funding agencies' requirements that increasingly require all data to be open access. For example, data generated during drilling operations (e.g. metadata from drilling, core and subsurface drilling, and borehole logs) will be stored on site in the ICDP mobile Drilling Information System (mDIS). Hence, we will apply both the F.A.I.R. (findable, accessible, interoperable, reusable) and C.A.R.E. (collective benefit, authority to control, responsibility, and ethics) guiding principles (Wilkinson et al., 2016; Carroll et al., 2020) for scientific data management and Indigenous data governance. This will also provide a proof of concept for future international drilling programmes.

5 Conclusion

The CALDERA workshop supported by the ICDP refined the scientific goals of the project idea and confirmed that scientific drilling is required to address these globally important science and societal goals. The OVC is an excellent setting to conduct the project, and we have articulated how findings at the OVC would be applied elsewhere. The workshop attendees reinforced the importance of studying the volcanic, tectonic, hydrological, and biosphere processes in connection rather than in isolation. Unravelling the changes through time and particularly the response of the system to volcanic or tectonic activity was deemed of high interest. It was agreed that the multi-disciplinary objectives and the natural complexity of the system require at least two boreholes: one shallow (< 200 m) focused on biosphere and groundwater, and one deep (1000–1500 m) focused on volcanic stratigraphy, tectonics, hydrology, and physical rock properties. Long-term monitoring provides opportunities to study the caldera–rift system in between and during times of volcanic or seismic activity. The workshop also introduced the participants to Māori world views and interests that are integral to the CALDERA project.

Karakia Whakawātea

Kia tau ngā manaakitanga a Te Mea Ngaro

Ki runga i tēnā, i tēnā o tātau

Kia mahea ai te hua mākihikihi

Kia toi te kupu, toi te mana, toi te whenua

Tūturu whakamaua kia tīna. Tīna!

Haumi e, Hui e, Tāiki e.

Bestow the blessings of the unseen force

upon each and everyone

Clear our path of any obstructions

And the words, the prestige and the land flourish

Indeed let it be affirmed!

Let it be binding, together, all in agreement

Code and data availability. No codes or datasets were used in this article.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/sd-33-67-2024-supplement.

Team list. Ludmila Adam (School of Environment, University of Auckland, Auckland, New Zealand), Hiroshi Asanuma (AIST, Fukushima, Japan), Jeff Ashby (Webster Drilling, Porirua, New Zealand), Jennifer Biddle (School of Marine Science and Policy, University of Delaware, Lewes, USA), Eric S. Boyd (Department of Microbiology and Cell Biology, Montana State University, Bozeman, USA), Andrea Brogi (Department of Earth and Geo-environmental Sciences, University of Bari Aldo Moro, Bari, Italy), S. Craig Cary (Thermophile Research Unit, University of Waikato, Hamilton, New Zealand), Corentin Caudron (Département Géosciences Environnement Société, Université Libre de Bruxelles, Bruxelles, Belgium), Daniel R. Colman (Department of Microbiology and Cell Biology, Montana State University, Bozeman, USA), Alysia Cox (Department of Chemistry & Geochemistry, Montana Technological University, Butte, USA), Penny Doorman (Bay Of Plenty Regional Council, Whakatāne, New Zealand), Jennifer Eccles (School of Environment, University of Auckland, Auckland, New Zealand), Mark Gibson (Department of Commercial and Business Partnerships, GNS Science, Taupō, New Zealand), Guido Giordano (University of Roma, Italy), Gino Gonzales (University of Bari Aldo Moro, Bari, Italy), Zayre Yvonne González Acevedo (Geology Department, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Ensenada, Mexico), Luke Goodwin (Webster Drilling, Porirua, New Zealand), Magnus Tumi Gudmundsson (Institute of Earth Sciences, School of Engineering and Natural Sciences, University of Iceland, Reykjavik, Iceland), John Hadfield (Waikato Regional Council, Hamilton, New Zealand), Kim Handley (Department of Biological Sciences, University of Auckland, Auckland, New Zealand), Ery Hughes (Department of Earth Structure and Processes, GNS Science, Lower Hutt, New Zealand), Finnigan Illsley-Kemp (School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand), Mark Ivamy (Bay Of Plenty Regional Council, Rotorua, New Zealand), Marie Jackson (Department of Geology and Geophysics, University of Utah, Salt Lake City, USA), Franziska Keller (Institute for Geochemistry and Petrology, ETH, Zurich, Switzerland), Geoff Kilgour (Department of Earth Structure and Processes, GNS Science, Taupō, New Zealand), Matteo Lelli (Institute of Geosciences and Earth Resources, IGG-CNR, Pisa Italy), Domenico Liotta (Department of Earth and Geo-environmental Sciences, University of Bari Aldo Moro, Bari; NRC,

Pisa, Italy), Haibo Liu (College of Earth Sciences, Jilin University, Jilin, China), Karen G. Lloyd (Department of Microbiology, University of Tennessee, Knoxville, USA), Katherine Luketina (Waikato Regional Council, Hamilton, New Zealand), Tiipene Marr (Te Mana o Ngāti Rangitihi, Whakatāne, New Zealand), Cécile Massiot (Department of Earth Resources and Materials, GNS Science, Lower Hutt, New Zealand), David D. McNamara (Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, UK), Sarah D. Milicich (Department of Earth Resources and Materials, GNS Science, Lower Hutt, New Zealand), Craig A. Miller (Department of Earth Structure and Processes, GNS Science, Taupō, New Zealand), Santanu Misra (Department of Earth Sciences, IITK, Uttar Pradesh, India), Giordano Montegrossi (Istituto di Geoscienze e Georisorse, IGG-CNR, Firenze, Italy), Madison Myers (Department of Earth Sciences, Montana State University, Bozeman, USA), Alexander R. L. Nichols (School of Earth and Environment, University of Canterbury, Christchurch, New Zealand), German Orozco (Department of Earth Resources and Materials, GNS Science, Taupō, New Zealand), Simona Pierdominici (Department of Geomechanics and Scientific Drilling, GFZ, Potsdam, Germany), Shane M. Rooyakkers (Department of Earth Resources and Materials, GNS Science, Lower Hutt, New Zealand), Monika Rusiecka (Institut des Sciences de la Terre, Université d'Orléans, Orléans, France), Anja Schleicher (Department of Inorganic and Isotope Geochemistry, GFZ, Potsdam, Germany), Douglas R. Schmitt (Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, USA), Brad Scott (Department of Earth Structure and Processes, GNS Science, Taupō, New Zealand), Andri Stefansson (School of Engineering and Natural Science, University of Iceland, Reykjavik, Iceland), John Stix (Department of Earth & Planetary Sciences, McGill University, Montreal, Canada), Matthew B. Stott (School of Biological Sciences, University of Canterbury, Christchurch, New Zealand), Camille Thomas (Université de Genève, Genève; Institute of Geological Sciences and Oeschger Centre for Climate Research, University of Bern, Switzerland), Kingan Tony (Webster Drilling, Porirua, New Zealand), John Townend (School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand), Pri Utami (Department of Geological Engineering, Gadjah Mada University, Yogyakarta, Indonesia), Kasper van Wijk (Department of Physics, University of Auckland, Auckland, New Zealand), Pilar Villamor (Department of Earth Structure and Processes, GNS Science, Lower Hutt, New Zealand), Pujun Wang (College of Earth Sciences, Jilin University, Jilin, China), Bain Webster (Webster Drilling, Porirua, New Zealand), Paul White (Department of Surface Geosciences, GNS Science, Taupō, New Zealand), Thomas Wiersberg (GFZ, Potsdam, Germany), Ralph Winmill (Contact Energy, Taupō, New Zealand), Zhuolong Yang (College of Earth Sciences, Jilin University, Jilin, China), Sadiq J. Zarrouk (Department of Engineering Science, University of Auckland, Auckland, New Zealand), Christian Zeeden (Department of petrophysics and borehole geophysics, Leibniz Institute for Applied Geophysics, Hannover, Germany), and Mariana Zuquim (Bay Of Plenty Regional Council, Whakatāne, New Zealand).

Author contributions. CM, LA, SCC, EH, GK, TM, SDM, CAM, ARLN, SMR, MBS, PV, and SJZ convened the workshop in Tauranga. All the co-authors contributed to the text and figures that resulted in the submission of a proposal. SMR, PV, EH, CAM, and JS focused on hypothesis 1; LA, DRS, ML, DL, AS, DDM, and SDM on hypothesis 2; and MBS, DRC, CT, ESB, SCC, and AC on hypothesis 3. EH compiled the Supplement. CM, CAM, CT, PV, and SP led the revisions, editing, and homogenisation of the final version of the paper. Participants at the workshop contributed intellectual input.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. Thanks to Ulrich Harms and the rest of the ICDP-OSG for advice on preparation of the workshop. We thank Tamati Waaka for the Karakia Whakawātea and all the iwi representatives who contributed to early discussions about the project. We acknowledge all the participants for their constructive input and enthusiasm. Thanks to Tomo Morishita for editorial handling, Mattia Pitstone for reviews, and an anonymous reviewer for their comments that helped improve the manuscript. Those interested in participating in future CALDERA activities are invited to contact the authors at caldera.drill@gns.cri.nz.

The authors of this paper wish to acknowledge with deep sadness the passing of one of our co-authors, S. Craig Cary. His enthusiasm and extensive expertise significantly contributed to the CALDERA project development since its early days, including for the ICDP workshop and this paper. He will be dearly missed.

Financial support. The workshop was largely funded by the International Continental Scientific Drilling Program, with additional support from Tourism New Zealand, Geodiscovery New Zealand, and the University of Waikato. The CALDERA project development was partially funded by New Zealand government funds through GNS Science's Strategic Science Investment Fund programme "Understanding the Te Riu-a-Māui/Zealandia Continent". A Toka Tū Ake EQC Biennial Grant supports a site survey and the associated community engagement.

Review statement. This paper was edited by Tomoaki Morishita and reviewed by Mattia Pistone and one anonymous referee.

References

Abe, K.: Seismicity of the caldera-making eruption of Mount Katmai, Alaska in 1912, B. Seismol. Soc. Am., 82, 175–191, https://pubs.geoscienceworld.org/ssa/bssa/article/82/1/175/

119528/Seismicity-of-the-caldera-making-eruption-of-Mount (last access: 18 March 2024), 1992.

Acocella, V.: Structural control on magmatism along divergent and convergent plate boundaries: Overview, model, problems, Earth Sci. Rev., 136, 226–288, https://doi.org/10.1016/j.earscirev.2014.05.006, 2014.

Acocella, V., Neri, M., Behncke, B., Bonforte, A., Del Negro, C., and Ganci, G.: Why Does a Mature Volcano Need New Vents? The Case of the New Southeast Crater at Etna, Front. Earth Sci., 4, 67, https://doi.org/10.3389/feart.2016.00067, 2016.

Allan, A. S. R., Wilson, C. J. N., Millet, M.-A., and Wysoczanski, R. J.: The invisible hand: Tectonic triggering and modulation of a rhyolitic supereruption, Geology, 40, 563–566, https://doi.org/10.1130/G32969.1, 2012.

Arnórsson, S.: Geothermal systems in Iceland: Structure and conceptual models – I. High-temperature areas, Geothermics, 24, 561–602, https://doi.org/10.1016/0375-6505(95)00025-9, 1995.

Bach, W., Peucker-Ehrenbrink, B., Hart, S. R., and Blusztajn, J. S.: Geochemistry of hydrothermally altered oceanic crust: DSDP/ODP Hole 504B – Implications for seawater-crust exchange budgets and Sr- and Pb-isotopic evolution of the mantle, Geochem. Geophy. Geosy., 4, 8904, https://doi.org/10.1029/2002GC000419, 2003.

Bannister, S., Bertrand, E. A., Heimann, S., Bourguignon, S., Asher, C., Shanks, J., and Harvison, A.: Imaging subcaldera structure with local seismicity, Okataina Volcanic Centre, Taupo Volcanic Zone, using double-difference seismic tomography, J. Volcanol. Geoth. Res., 431, 107653, https://doi.org/10.1016/j.jvolgeores.2022.107653, 2022.

Barker, S. J., Rowe, M. C., Wilson, C. J. N., Gamble, J. A., Rooyakkers, S. M., Wysoczanski, R. J., Illsley-Kemp, F., and Kenworthy, C. C.: What lies beneath? Reconstructing the primitive magmas fueling voluminous silicic volcanism using olivine-hosted melt inclusions, Geology, 48, 504–508, https://doi.org/10.1130/G47422.1, 2020.

Barry, P. H., de Moor, J. M., Giovannelli, D., Schrenk, M., Hummer, D. R., Lopez, T., Pratt, C. A., Segura, Y. A., Battaglia, A., Beaudry, P., Bini, G., Cascante, M., d'Errico, G., di Carlo, M., Fattorini, D., Fullerton, K., Gazel, E., González, G., Halldórsson, S. A., Iacovino, K., Ilanko, T., Kulongoski, J. T., Manini, E., Martínez, M., Miller, H., Nakagawa, M., Ono, S., Patwardhan, S., Ramírez, C. J., Regoli, F., Smedile, F., Turner, S., Vetriani, C., Yücel, M., Ballentine, C. J., Fischer, T. P., Hilton, D. R., and Lloyd, K. G.: Forearc carbon sink reduces long-term volatile recycling into the mantle, Nature, 568, 487–492, https://doi.org/10.1038/s41586-019-1131-5, 2019.

Battaglia, M., Troise, C., Obrizzo, F., Pingue, F., and De Natale, G.: Evidence for fluid migration as the source of deformation at Campi Flegrei caldera (Italy), Geophys. Res. Lett., 33, L01307, https://doi.org/10.1029/2005GL024904, 2006.

Benson, T. W., Illsley-Kemp, F., Elms, H. C., Hamling, I. J., Savage, M. K., Wilson, C. J. N., Mestel, E. R. H., and Barker, S. J.: Earthquake Analysis Suggests Dyke Intrusion in 2019 Near Tarawera Volcano, New Zealand, Front. Earth Sci., 8, 606992, https://doi.org/10.3389/feart.2020.606992, 2021.

Berryman, K., Villamor, P., Nairn, I., van Dissen, R., Begg, J., and Lee, J.: Late Pleistocene surface rupture history of the Paeroa Fault, Taupo Rift, New Zealand, New Zeal. J. Geol. Geop., 51, 135–158, https://doi.org/10.1080/00288300809509855, 2008.

Berryman, K., Villamor, P., Nairn, I., Begg, J., Alloway, B. V, Rowland, J., Lee, J., and Capote, R.: Volcano-tectonic interactions at the southern margin of the Okataina Volcanic Centre, Taupō Volcanic Zone, New Zealand, J. Volcanol. Geoth. Res., 427, 107552, https://doi.org/10.1016/j.jvolgeores.2022.107552, 2022.

Bertrand, E. A., Kannberg, P., Caldwell, T. G., Heise, W., Constable, S., Scott, B., Bannister, S., Kilgour, G., Bennie, S. L., Hart, R., and Palmer, N.: Inferring the magmatic roots of volcano-geothermal systems in the Rotorua Caldera and Okataina Volcanic Centre from magnetotelluric models, J. Volcanol. Geoth. Res., 431, 107645, https://doi.org/10.1016/j.jvolgeores.2022.107645, 2022.

Bouvet de Maisonneuve, C., Forni, F., and Bachmann, O.: Magma reservoir evolution during the build up to and recovery from caldera-forming eruptions – A generalizable model?, Earth Sci. Rev., 218, 103684, https://doi.org/10.1016/j.earscirev.2021.103684, 2021.

Bursik, M., Renshaw, C., McCalpin, J., and Berry, M.: A volcanotectonic cascade: Activation of range front faulting and eruptions by dike intrusion, Mono Basin-Long Valley Caldera, California, J. Geophys. Res.-Sol. Ea., 108, 2393, https://doi.org/10.1029/2002JB002032, 2003.

Byerlee, J. D. and Savage, J. C.: Coulomb plasticity within the fault zone, Geophys. Res. Lett., 19, 2341–2344, https://doi.org/10.1029/92GL02370, 1992.

Cabaniss, H. E., Gregg, P. M., and Grosfils, E. B.: The Role of Tectonic Stress in Triggering Large Silicic Caldera Eruptions, Geophys. Res. Lett., 45, 3889–3895, https://doi.org/10.1029/2018GL077393, 2018.

Carroll, S. R., Garba, I., Figueroa-Rodríguez, O. L., Holbrook, J., Lovett, R., Materechera, S., Parsons, M., Raseroka, K., Rodriguez-Lonebear, D., and Rowe, R.: The CARE principles for indigenous data governance, Data Sci. J., 19, 43, https://doi.org/10.5334/dsj-2020-043, 2020.

Carson, L. B., Miller, C. A., Massiot, C., Villamor, P., Leonard, G. S., and Alcaraz, S. A.: 3D visualisation model of the basement geology and caldera structure at Okataina Volcanic Centre, in: Geoscience Society of New Zealand Annual Conference, 29 November–1 December 2022, Massey University, Palmerston North, New Zealand, edited by: Zernack, A. V. and Palmer, J., Geoscience Society of New Zealand, Wellington, NZ, 161A, ISBN 978-0-473-66216-5, 2022.

Casar, C. P., Kruger, B. R., Flynn, T. M., Masterson, A. L., Momper, L. M., and Osburn, M. R.: Mineral-hosted biofilm communities in the continental deep subsurface, Deep Mine Microbial Observatory, SD, USA, Geobiology, 18, 508–522, https://doi.org/10.1111/gbi.12391, 2020.

Cassidy, M., Sandberg, A., and Mani, L.: The Ethics of Volcano Geoengineering, Earths Future, 11, 1–17, https://doi.org/10.1029/2023EF003714, 2023.

Chamberlain, C. J., Boese, C. M., Eccles, J. D., Savage, M. K., Baratin, L. M., Townend, J., Gulley, A. K., Jacobs, K. M., Benson, A., Taylor-Offord, S., and Thurber, C.: Real-time earthquake monitoring during the second phase of the deep fault drilling project, Alpine Fault, New Zealand, Seismol. Res. Lett., 88, 1443–1454, https://doi.org/10.1785/0220170095, 2017.

Cluff, M. A., Hartsock, A., MacRae, J. D., Carter, K., and Mouser, P. J.: Temporal Changes in Microbial Ecology and Geochemistry in Produced Water from Hydraulically Fractured Marcel-lus Shale Gas Wells, Environ. Sci. Technol., 48, 6508–6517, https://doi.org/10.1021/es501173p, 2014.

Cole, J. W., Deering, C. D., Burt, R. M., Sewell, S., Shane, P. A. R., and Matthews, N. E.: Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand: A review of volcanism and synchronous pluton development in an active, dominantly silicic caldera system, Earth Sci. Rev., 128, 1–17, https://doi.org/10.1016/j.earscirev.2013.10.008, 2014.

Colman, D. R., Lindsay, M. R., and Boyd, E. S.: Mixing of meteoric and geothermal fluids supports hyperdiverse chemosynthetic hydrothermal communities, Nat. Commun., 10, 681, https://doi.org/10.1038/s41467-019-08499-1, 2019.

Colman, D. R., Lindsay, M. R., Harnish, A., Bilbrey, E. M., Amenabar, M. J., Selensky, M. J., Fecteau, K. M., Debes II, R. V, Stott, M. B., Shock, E. L., and Boyd, E. S.: Seasonal hydrologic and geologic forcing drive hot spring geochemistry and microbial biodiversity, Environ. Microbiol., 23, 4034–4053, https://doi.org/10.1111/1462-2920.15617, 2021.

Colman, D. R., Amenabar, M. J., Fernandes-Martins, M. C., and Boyd, E. S.: Subsurface Archaea associated with rapid geobiological change in a model Yellowstone hot spring, Commun. Earth. Environ., 3, 205, https://doi.org/10.1038/s43247-022-00542-2, 2022.

Corti, G.: Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System, Tectonophysics, 522–523, 1–33, https://doi.org/10.1016/j.tecto.2011.06.010, 2012.

Costa, F.: Clocks in magmatic rocks, Annu. Rev. Earth. Planet Sci., 49, 231–252, https://doi.org/10.1146/annurev-earth-080320-060708, 2021.

De Natale, G., Troise, C., Mark D, Mormone, A., Piochi, M., Di Vito, M. A., Isaia, R., Carlino, S., Barra, D., and Somma, R.: The Campi Flegrei Deep DrillingProject (CFDDP): New insight on caldera structure, evolution and hazard implications for the Naples area (Southern Italy), Geochem. Geophy. Geosy., 17, 4836–4847, https://doi.org/10.1002/2015GC006183, 2016.

de Ronde, C. E. J., Humphris, S. E., Höfig, T. W., and Reyes, A. G.: Critical role of caldera collapse in the formation of seafloor mineralization: The case of Brothers volcano, Geology, 47, 762–766, https://doi.org/10.1130/G46047.1, 2019.

Druitt, T., Kutterolf, S., and Höfig, T. W.: Expedition 398 Scientific Prospectus: Hellenic Arc Volcanic Field, International Ocean Discovery Program, https://doi.org/10.14379/iodp.sp.398.2022, 2022.

Ellis, S., Heise, W., Kissling, W., Villamor, P., and Schreurs, G.: The effect of crustal melt on rift dynamics: case study of the Taupo Volcanic Zone, New Zeal. J. Geol. Geop., 57, 453–458, https://doi.org/10.1080/00288306.2014.972961, 2014.

Erzinger, J., Wiersberg, T., and Zimmer, M.: Real-time mud gas logging and sampling during drilling, Geofluid, 6, 225–233, https://doi.org/10.1111/j.1468-8123.2006.00152.x, 2006.

Falkowski, P. G., Fenchel, T., and Delong, E. F.: The Microbial Engines That Drive Earth's Biogeochemical Cycles, Science, 320, 1034–1039, https://doi.org/10.1126/science.1153213, 2008.

Fournier, R. O.: Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment, Econ. Geol., 94, 1193–1211, https://doi.org/10.2113/gsecongeo.94.8.1193, 1999.

Freifeld, B. M., Trautz, R. C., Kharaka, Y. K., Phelps, T. J., Myer, L. R., Hovorka, S. D., and Collins, D. J.: The U-tube: A novel system for acquiring borehole fluid samples from a deep geologic CO_2 sequestration experiment, J. Geophys. Res.-Sol. Ea., 110, B10203, https://doi.org/10.1029/2005JB003735, 2005.

Fullerton, K. M., Schrenk, M. O., Yücel, M., Manini, E., Basili, M., Rogers, T. J., Fattorini, D., Di Carlo, M., d'Errico, G., Regoli, F., Nakagawa, M., Vetriani, C., Smedile, F., Ramírez, C., Miller, H., Morrison, S. M., Buongiorno, J., Jessen, G. L., Steen, A. D., Martínez, M., de Moor, J. M., Barry, P. H., Giovannelli, D., and Lloyd, K. G.: Effect of tectonic processes on biosphere–geosphere feedbacks across a convergent margin, Nat. Geosci., 14, 301–306, https://doi.org/10.1038/s41561-021-00725-0, 2021.

Giggenbach, W. F.: Variations in the chemical and isotopic composition of fluids discharged from the Taupo Volcanic Zone, New Zealand, J. Volcanol. Geoth. Res., 68, 89–116, https://doi.org/10.1016/0377-0273(95)00009-J, 1995.

Gold, T.: The deep, hot biosphere, P. Natl. Acad. Sci. USA, 89, 6045–6049, https://doi.org/10.1073/pnas.89.13.6045, 1992.

Gottsmann, J., Carniel, R., Coppo, N., Wooller, L., Hautmann, S., and Rymer, H.: Oscillations in hydrothermal systems as a source of periodic unrest at caldera volcanoes: Multiparameter insights from Nisyros, Greece, Geophys. Res. Lett., 34, L07307, https://doi.org/10.1029/2007GL029594, 2007.

Grindley, G. W.: Geology and structure of Waiotapu geothermal field, New Zealand Department of Scientific and Industrial Research bulletin, 155, 10–25, 1963.

Hayba, D. O. and Ingebritsen, S. E.: Multiphase groundwater flow near cooling plutons, J. Geophys. Res.-Sol. Ea., 102, 12235–12252, https://doi.org/10.1029/97JB00552, 1997.

Heap, M. J. and Violay, M. E. S.: The mechanical behaviour and failure modes of volcanic rocks: a review, B. Volcanol., 83, 33, https://doi.org/10.1007/s00445-021-01447-2, 2021.

Heap, M. J., Troll, V. R., Kushnir, A. R. L., Gilg, H. A., Collinson, A. S. D., Deegan, F. M., Darmawan, H., Seraphine, N., Neuberg, J., and Walter, T. R.: Hydrothermal alteration of andesitic lava domes can lead to explosive volcanic behaviour, Nat. Commun., 10, 5063, https://doi.org/10.1038/s41467-019-13102-8, 2019.

Hikuroa, D.: Mātauranga Māori – the ūkaipō of knowledge in New Zealand, J. Roy. Soc. New Zeal., 47, 5–10, https://doi.org/10.1080/03036758.2016.1252407, 2017.

Hildreth, W.: The timing of caldera collapse at Mount Katmai in response to magma withdrawal toward Novarupta, Geophys. Res. Lett., 18, 1541–1544, https://doi.org/10.1029/91GL01083, 1991.

Hill, D. P., Pollitz, F., and Newhall, C.: Earthquake–volcano interactions, Phys. Today, 55, 41–47, https://doi.org/10.1063/1.1535006, 2002.

Hilley, G. E., Brodsky, E.E., Roman, D., Shillington, D. J., Brudzinski, M., Behn, M., Tobin, H., and the SZ4D RCN: SZ4D Implementation Plan, edited by: Hilley, G. E., Stanford Digital Repository, https://doi.org/10.25740/hy589fc7561, 2022.

Houghton, B. F., Wilson, C. J. N., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., Briggs, R. M., and Pringle, M. S.: Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand, Geology, 23, 13–16, https://doi.org/10.1130/0091-7613(1995)023<0013:CADOAL>2.3.CO;2, 1995.

Hughes, E. C., Mazot, A., Kilgour, G., Asher, C., Michelini, M., Britten, K., Chardot, L., Feisel, Y., and Werner, C.: Understanding degassing pathways along the 1886 Tarawera (New Zealand) volcanic fissure by combining soil and lake CO_2 fluxes, Front. Earth Sci., 7, 264, https://doi.org/10.3389/feart.2019.00264, 2019.

Hughes, G. R. and Mahood, G. A.: Silicic calderas in arc settings: Characteristics, distribution, and tectonic controls, Bulletin, 123, 1577–1595, https://doi.org/10.1130/B30232.1, 2011.

Hutnak, M., Hurwitz, S., Ingebritsen, S. E., and Hsieh, P. A.: Numerical models of caldera deformation: Effects of multiphase and multicomponent hydrothermal fluid flow, J. Geophys. Res.-Sol. Ea., 114, B04411, https://doi.org/10.1029/2008JB006151, 2009.

Ilic, O., Sigmundsson, F., Lavallée, Y., Mortensen, A. K., Eichelberger, J., Markusson, S. H., Papale, P., and Thordarson, T.: Geological Risk Associated with Drilling into Magma at Krafla Caldera, Iceland: Preliminary Evaluation, in: Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland and online, April–October 2021, International Geothermal Association, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/12145.pdf (last access: 18 March 2024), 2021.

Illsley-Kemp, F., Barker, S. J., Wilson, C. J. N., Chamberlain, C. J., Hreinsdóttir, S., Ellis, S., Hamling, I. J., Savage, M. K., Mestel, E. R. H., and Wadsworth, F. B.: Volcanic Unrest at Taupō Volcano in 2019: Causes, Mechanisms and Implications, Geochem., Geophy. Geosy. 22, e2021GC009803, https://doi.org/10.1029/2021GC009803, 2021.

Jolie, E., Klinkmueller, M., Moeck, I., and Bruhn, D.: Linking gas fluxes at Earth's surface with fracture zones in an active geothermal field, Geology, 44, 187–190, https://doi.org/10.1130/G37412.1, 2016.

Jolie, E., Scott, S., Faulds, J., Chambefort, I., Axelsson, G., Gutiérrez-Negrín, L. C., Regenspurg, S., Ziegler, M., Ayling, B., and Richter, A.: Geological controls on geothermal resources for power generation, Nat. Rev. Earth Environ., 2, 324–339, https://doi.org/10.1038/s43017-021-00154-y, 2021.

Kanakiya, S., Turner, G. M., Rowe, M. C., Adam, L., and Lindsay, J. M.: High remanent magnetization measured in hydrothermally altered lavas, Geophys. Res. Lett., 48, e2021GL095732, https://doi.org/10.1029/2021GL095732, 2021a.

Kanakiya, S., Adam, L., Rowe, M. C., Lindsay, J. M., and Esteban, L.: The role of tuffs in sealing volcanic conduits, Geophys. Res. Lett., 48, e2021GL095175, https://doi.org/10.1029/2021GL095175, 2021b.

Kennedy, B. M., Farquhar, A., Hilderman, R., Villeneuve, M. C., Heap, M. J., Mordensky, S., Kilgour, G., Jolly, Art., Christenson, B., and Reuschlé, T.: Pressure Controlled Permeability in a Conduit Filled with Fractured Hydrothermal Breccia Reconstructed from Ballistics from Whakaari (White Island), New Zealand, Geosciences, 10, 138, https://doi.org/10.3390/geosciences10040138, 2020.

Komori, S., Kagiyama, T., Takakura, S., Ohsawa, S., Mimura, M., and Mogi, T.: Effect of the hydrothermal alteration on the surface conductivity of rock matrix: comparative study between relatively-high and low temperature hydrothermal systems, J. Volcanol. Geoth. Res., 264, 164–171, https://doi.org/10.1016/j.jvolgeores.2013.08.009, 2013.

Kukutai, T., Campbell-Kamariera, K., Mead, A., Mikaere, K., Moses, C., Whitehead, J., and Cormack, D.: Māori data governance model, Te Kāhui Raraunga, https://tengira.waikato.ac.nz/__data/assets/pdf_file/0008/973763/Maori_Data_Governance_Model.pdf (last access: 18 March 2024), 2023.

Lahitte, P., Gillot, P.-Y., and Courtillot, V.: Silicic central volcanoes as precursors to rift propagation: the Afar case, Earth Planet Sci. Lett., 207, 103–116, https://doi.org/10.1016/S0012-821X(02)01130-5, 2003.

Lazrus, H., Maldonado, J., Blanchard, P., Souza, M. K., Thomas, B., and Wildcat, D.: Culture change to address climate change: Collaborations with Indigenous and Earth sciences for more just, equitable, and sustainable responses to our climate crisis, PLOS Climate, 1, e0000005, https://doi.org/10.1371/journal.pclm.0000005, 2022.

Linde, A. T. and Sacks, I. S.: Triggering of volcanic eruptions, Nature, 395, 888–890, https://doi.org/10.1038/27650, 1998.

Lithgow, R., Massiot, C., Bertrand, E., Heise, W., Miller, C. A., Bennie, S., Brakenrig, T., Coup, L., and Macdonald, N.: Interpretation of geophysical data from the eastern margin of the Okataina Volcanic Centre (Issue October), GNS Science, Lower Hutt, NZ, https://doi.org/10.21420/FPEK-CG53, 2022.

Lowenstern, J. B., Smith, R. B., and Hill, D. P.: Monitoring supervolcanoes: geophysical and geochemical signals at Yellowstone and other large caldera systems, Philos. t. roy. soc. A, 364, 2055–2072, https://doi.org/10.1098/rsta.2006.1813, 2006.

Lowenstern, J. B., Bergfeld, D., Evans, W. C., and Hunt, A. G.: Origins of geothermal gases at Yellowstone, J. Volcanol. Geoth. Res., 302, 87–101, https://doi.org/10.1016/j.jvolgeores.2015.06.010, 2015.

Lund, J. W., Huttrer, G. W., and Toth, A. N.: Characteristics and trends in geothermal development and use, 1995 to 2020, Geothermics, 105, 102522, https://doi.org/10.1016/j.geothermics.2022.102522, 2022.

Magnabosco, C., Lin, L. H., Dong, H., Bomberg, M., Ghiorse, W., Stan-Lotter, H., Pedersen, K., Kieft, T. L., van Heerden, E., and Onstott, T. C.: The biomass and biodiversity of the continental subsurface, Nat. Geosci., 11, 707–717, https://doi.org/10.1038/s41561-018-0221-6, 2018.

Mahony, S. H., Wallace, L. M., Miyoshi, M., Villamor, P., Sparks, R. S. J., and Hasenaka, T.: Volcano-tectonic interactions during rapid plate-boundary evolution in the Kyushu region, SW Japan, Bulletin, 123, 2201–2223, https://doi.org/10.1130/B30408.1, 2011.

Marzocchi, W.: Remote seismic influence on large explosive eruptions, J. Geophys. Res.-Sol. Ea., 107, EPM 6-1–EPM 6-7, https://doi.org/10.1029/2001JB000307, 2002.

Mazot, A., Schwandner, F. M., Christenson, B., De Ronde, C. E., Inguaggiato, S., Scott, B., Graham, D., Britten, K., Keeman, J., and Tan, K.: CO_2 discharge from the bottom of volcanic Lake Rotomahana, New Zealand, Geochem. Geophy. Geosy., 15, 577–588, https://doi.org/10.1002/2013GC004945, 2014.

McNamara, D. D., Lister, A., and Prior, D. J.: Calcite sealing in a fractured geothermal reservoir: Insights from combined EBSD and chemistry mapping, J. Volcanol. Geoth. Res., 323, 38–52, https://doi.org/10.1016/j.jvolgeores.2016.04.042, 2016.

McNamara, D. D., Milicich, S. D., Massiot, C., Villamor, P., McLean, K., Sépulveda, F., and Ries, W. F.: Tectonic Controls on Taupo Volcanic Zone Geothermal Expression: Insights From Te Mihi, Wairakei Geothermal Field, Tectonics, 38, 3011–3033, https://doi.org/10.1029/2018TC005296, 2019.

Miller, C. A. and Jolly, A. D.: A model for developing best practice volcano monitoring: A combined threat assessment, consultation and network effectiveness approach, Nat. Hazards, 71, 493–522, https://doi.org/10.1007/s11069-013-0928-z, 2014.

Miller, C. A., Taylor-Offord, S., Sherburn, S., Magill, C. R., and Pastor-Paz, J.: Revised threat assessment of New Zealand's volcanoes, GNS Science, Lower Hutt (NZ), GNS Science report; 2022/41, 32 pp., https://doi.org/10.21420/AQWM-ZR12, 2022a.

Miller, C. A., Barretto, J., Stagpoole, V., Caratori-Tontini, F., Brakenrig, T., and Bertrand, E.: The integrated history of repeated caldera formation and infill at the Okataina Volcanic Centre: Insights from 3D gravity and magnetic models, J. Volcanol. Geoth. Res., 427, 107555, https://doi.org/10.1016/j.jvolgeores.2022.107555, 2022b.

Mordensky, S. P., Villeneuve, M. C., Farquharson, J. I., Kennedy, B. M., Heap, M. J., and Gravley, D. M.: Rock mass properties and edifice strength data from Pinnacle Ridge, Mt. Ruapehu, New Zealand, J. Volcanol. Geoth. Res., 367, 46–62, https://doi.org/10.1016/j.jvolgeores.2018.09.012, 2018.

Mordensky, S. P., Heap, M. J., Kennedy, B. M., Gilg, H. A., Villeneuve, M. C., Farquharson, J. I., and Gravley, D. M.: Influence of alteration on the mechanical behaviour and failure mode of andesite: implications for shallow seismicity and volcano monitoring, B. Volcanol., 81, 1–12, https://doi.org/10.1007/s00445-019-1306-9, 2019.

Morgavi, D., Arienzo, I., Montagna, C., Perugini, D., and Dingwell, D. B.: Magma mixing: history and dynamics of an eruption trigger, in: Volcanic Unrest, edited by: Gottsmann, J., Neuberg, J., and Scheu, B., Springer Open, 123–137, https://doi.org/10.1007/978-3-319-58412-6, 2017.

Mosser, J. L., Mosser, A. G., and Brock, T. D.: Bacterial origin of sulfuric acid in geothermal habitats, Science, 179, 1323–1324, https://doi.org/10.1126/science.179.4080.1323, 1973.

Mu, A. and Moreau, J. W.: The geomicrobiology of CO_2 geosequestration: a focused review on prokaryotic community responses to field-scale CO_2 injection, Front. Microbiol., 6, 263, https://doi.org/10.3389/fmicb.2015.00263, 2015.

Muirhead, J. D., Illsley-Kemp, F., Barker, S. J., Villamor, P., Wilson, C. J. N., Otway, P., Mestel, E. R. H., Leonard, G. S., Ellis, S., Savage, M. K., Bannister, S., Rowland, J. V, Townsend, D., Hamling, I. J., Hreinsdóttir, S., Smith, B., McGregor, R., Snowden, M., and Shalla, Y.: Stretching, Shaking, Inflating: Volcanic-Tectonic Interactions at a Rifting Silicic Caldera, Front. Earth Sci., 10, 835841, https://doi.org/10.3389/feart.2022.835841, 2022.

Nairn, I. A.: Geology of the Okataina Volcanic Centre, scale 1 : 50 000, Institute of Geological and Nuclear Sciences Limited, ISBN 0478097182, 2002.

New Zealand Active Faults Database: 2003–, GNS Science, Lower Hutt (NZ), http://gns.cri.nz/Home/Products/Databases/Active-Faults-Database-of-New-Zealand (last access: 22 September 2023), 2003.

Nicolas, A., Lévy, L., Sissmann, O., Li, Z., Fortin, J., Gibert, B., and Sigmundsson, F.: Influence of hydrothermal alteration on the elastic behaviour and failure of heat-treated andesite from Guadeloupe, Geophys. J. Int., 223, 2038–2053, https://doi.org/10.1093/gji/ggaa437, 2020.

Nordstrom, D. K., Ball, J. W., and McCleskey, R. B.: Ground water to surface water: chemistry of thermal outflows in Yellowstone National Park, Geothermal biology and geochemistry in Yellowstone National Park, Open File Report, Montana State University, Bozeman, Montana, USA, 73–94, https://pubs.usgs.gov/publication/70198852 (last access: 18 March 2024), 2005.

Norini, G., Carrasco-Núñez, G., Corbo-Camargo, F., Lermo, J., Rojas, J. H., Castro, C., Bonini, M., Montanari, D., Corti, G., Moratti, G., Piccardi, L., Chavez, G., Zuluaga, M. C., Ramirez, M., and Cedillo, F.: The structural architecture of the Los Humeros volcanic complex and geothermal field, J. Volcanol. Geoth. Res., 381, 312–329, https://doi.org/10.1016/j.jvolgeores.2019.06.010, 2019.

Oliva, S. J., Ebinger, C. J., Wauthier, C., Muirhead, J. D., Roecker, S. W., Rivalta, E., and Heimann, S.: Insights into fault-magma interactions in an early-stage continental rift from source mechanisms and correlated volcano-tectonic earthquakes, Geophys. Res. Lett., 46, 2065–2074, https://doi.org/10.1029/2018GL080866, 2019.

Payne, D., Dunham, E. C., Mohr, E., Miller, I., Arnold, A., Erickson, R., Fones, E. M., Lindsay, M. R., Colman, D. R., and Boyd, E. S.: Geologic legacy spanning > 90 years explains unique Yellowstone hot spring geochemistry and biodiversity, Environ. Microbiol., 21, 4180–4195, https://doi.org/10.1111/1462-2920.14775, 2019.

Pearson-Grant, S., Miller, C. A., Carson, L. B., Bertrand, E. A., and Leonard, G. S.: Influences on geothermal circulation in the Okataina Volcanic Centre, New Zealand, J. Volcanol. Geoth. Res., 432, 107705, https://doi.org/10.1016/j.jvolgeores.2022.107705, 2022.

Plag, H. P., Brocklebank, S., Brosnan, D., Campus, P., Cloetingh, S., Jules-Plag, S., and Stein, S.: Extreme Geohazards: Reducing Disaster Risk and Increasing Resilience, European Science Fundation, 72 pp., ISBN 978-2-36873-197-0, http://archives.esf.org/fileadmin/Public_documents/Publications/Natural_Hazards.pdf (last access: 18 March 2024), 2015.

Pola, A., Crosta, G. B., Fusi, N., and Castellanza, R.: General characterization of the mechanical behaviour of different volcanic rocks with respect to alteration, Eng. Geol., 169, 1–13, https://doi.org/10.1016/j.enggeo.2013.11.011, 2014.

Polom, U., Mueller, C., Nicol, A., Villamor, P., Langridge, R. M., and Begg, J. G.: Finding the Concealed Section of the Whakatane Fault in the Whakatane Township with a Shear Wave Land Streamer System: A Seismic Surveying Report, Institute of Geological & Nuclear Sciences, ISBN 978-0-947510-76-3, 2016.

Power, J. F., Carere, C. R., Lee, C. K., Wakerley, G. L. J., Evans, D. W., Button, M., White, D., Climo, M. D., Hinze, A. M., and Morgan, X. C.: Microbial biogeography of 925 geothermal springs in New Zealand, Nat. Commun., 9, 2876, https://doi.org/10.1038/s41467-018-05020-y, 2018.

Power, J. F., Lowe, C. L., Carere, C. R., McDonald, I. R., Cary, S. C., and Stott, M. B.: Temporal dynamics of geothermal microbial communities in Aotearoa-New Zealand, Front. Microbiol., 14, 1094311, https://doi.org/10.3389/fmicb.2023.1094311, 2023.

Power, J. F., Carere, C. R., Welford, H. E., Hudson, D. T., Lee, K. C., Moreau, J. W., Ettema, T. J., Reysenbach, A. L., Lee, C. K., Colman, D. R., and Boyd, E. S.: A genus in the bacterial phylum Aquificota appears to be endemic to Aotearoa-New Zealand, Nat.

Commun., 15, 179, https://doi.org/10.1038/s41467-023-43960-2, 2024.

Rosenberg, M. D., Wilson, C. J. N., Bignall, G., Ireland, T. R., Sepulveda, F., and Charlier, B. L. A.: Structure and evolution of the Wairakei–Tauhara geothermal system (Taupo Volcanic Zone, New Zealand) revisited with a new zircon geochronology, J. Volcanol. Geoth. Res., 390, 106705, https://doi.org/10.1016/j.jvolgeores.2019.106705, 2020.

Rowe, M. C., Carey, R. J., White, J. D. L., Kilgour, G., Hughes, E., Ellis, B., Rosseel, J.-B., and Segovia, A.: Tarawera 1886: an integrated review of volcanological and geochemical characteristics of a complex basaltic eruption, New Zeal. J. Geol. Geop., 64, 296–319, https://doi.org/10.1080/00288306.2021.1914118, 2021.

Rowland, J. V. and Simmons, S. F.: Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits, Econ. Geol., 107, 427–457, https://doi.org/10.2113/econgeo.107.3.427, 2012.

Rowland, J. V., Wilson, C. J. N., and Gravley, D. M.: Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand, J. Volcanol. Geoth. Res., 190, 89–108, https://doi.org/10.1016/j.jvolgeores.2009.05.004, 2010.

Ruz-Ginouves, J., Gerbault, M., Cembrano, J., Iturrieta, P., Leiva, F. S., Novoa, C., and Hassani, R.: The interplay of a fault zone and a volcanic reservoir from 3D elasto-plastic models: Rheological conditions for mutual trigger based on a field case from the Andean Southern Volcanic Zone, J. Volcanol. Geoth. Res., 418, 107317, https://doi.org/10.1016/j.jvolgeores.2021.107317, 2021.

Sanderson, D. J. and Nixon, C. W.: The use of topology in fracture network characterization, J. Struct. Geol., 72, 55–66, https://doi.org/10.1016/j.jsg.2015.01.005, 2015.

Scarpa, R., Bianco, F., Capuano, P., Castellano, M., D'Auria, L., Di Lieto, B., and Romano, P.: Historic unrest of the Campi Flegrei Caldera, Italy, in: Campi Flegrei: A Restless Caldera in a Densely Populated Area, edited by: Orsi, G., D'Antonio, M., and Civetta, L., Springer, Berlin, Heidelberg, 257–282, https://doi.org/10.1007/978-3-642-37060-1_10, 2022.

Scott, S., Driesner, T., and Weis, P.: Geologic controls on supercritical geothermal resources above magmatic intrusions, Nat. Commun., 6, 7837, https://doi.org/10.1038/ncomms8837, 2015.

Self, S.: The effects and consequences of very large explosive volcanic eruptions, Philos. T. Roy. Soc. A, 364, 2073–2097, https://doi.org/10.1098/rsta.2006.1814, 2006.

Shapiro, N. M., Droznin, D. V, Droznina, S. Y., Senyukov, S. L., Gusev, A. A., and Gordeev, E. I.: Deep and shallow long-period volcanic seismicity linked by fluid-pressure transfer, Nat. Geosci., 10, 442–445, https://doi.org/10.1038/ngeo2952, 2017.

Sherburn, S., Bromley, C., Bannister, S., Sewell, S. M., and Bourguignon, S.: New Zealand Geothermal Induced Seismicity: an overview, in: Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015, edited by: Horne, R. and Boyd, T., International Geothermal Association, 24009, 9 pp. , https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/24009.pdf (last access: 18 March 2024), 2015a.

Sherburn, S., Sewell, S. M., Bourguignon, S., Cumming, W., Bannister, S., Bardsley, C., Winick, J., Quinao, J., and Wallis, I. C.: Microseismicity at Rotokawa geothermal field, New Zealand, 2008—2012, Geothermics, 54, 23–34, https://doi.org/10.1016/j.geothermics.2014.11.001, 2015b.

Sibson, R. H.: Fluid involvement in normal faulting, J. Geodyn., 29, 469–499, https://doi.org/10.1016/S0264-3707(99)00042-3, 2000.

Simmons, S. F., Brown, K. L., Browne, P. R. L., and Rowland, J. V.: Gold and silver resources in Taupo Volcanic Zone geothermal systems, Geothermics, 59, 205–214, https://doi.org/10.1016/j.geothermics.2015.07.009, 2016.

Simpson, M. P. and Bignall, G.: Undeveloped high-enthalpy geothermal fields of the Taupo Volcanic Zone, New Zealand, Geothermics, 59, 325–346, https://doi.org/10.1016/j.geothermics.2015.08.006, 2016.

Somr, M., Žák, J., Kabele, P., and Tomek, F.: Analysis of fracturing processes leading to caldera collapse, Earth Sci. Rev., 241, 104413, https://doi.org/10.1016/j.earscirev.2023.104413, 2023.

Sparks, R. S. J.: Forecasting volcanic eruptions, Earth Planet. Sci. Lett., 210, 1–15, https://doi.org/10.1016/S0012-821X(03)00124-9, 2003.

Sparks, R. S. J., Blundy, J. D., Cashman, K. V., Jackson, M., Rust, A., and Wilson, C. J. N.: Large silicic magma bodies and very large magnitude explosive eruptions, B. Volcanol., 84, 4–9, https://doi.org/10.1007/s00445-021-01510-y, 2022.

Stagpoole, V., Miller, C., Caratori Tontini, F., Brakenrig, T., and Macdonald, N.: A two million-year history of rifting and caldera volcanism imprinted in new gravity anomaly compilation of the Taupō Volcanic Zone, New Zealand, New Zeal. J. Geol. Geop., 64, 358–371, https://doi.org/10.1080/00288306.2020.1848882, 2021.

Stein, R. S.: The role of stress transfer in earthquake occurrence, Nature, 402, 605–609, https://doi.org/10.1038/45144, 1999.

Stone, J., Edgar, J. O., Gould, J. A., and Telling, J.: Tectonically-driven oxidant production in the hot biosphere, Nat. Commun., 13, 4529, https://doi.org/10.1038/s41467-022-32129-y, 2022.

Taute, N., Morgan, K., Ingham, J., Archer, R., and Fa'aui, T.: Māori values in geothermal management and development, AlterNative, 18, 548–555, https://doi.org/10.1177/11771801221118629, 2022.

Telling, J., Boyd, E. S., Bone, N., Jones, E. L., Tranter, M., MacFarlane, J. W., Martin, P. G., Wadham, J. L., Lamarche-Gagnon, G., Skidmore, M. L., Hamilton, T. L., Hill, E., Jackson, M., and Hodgson, D. A.: Rock comminution as a source of hydrogen for subglacial ecosystems, Nat. Geosci., 8, 851–855, https://doi.org/10.1038/ngeo2533, 2015.

Templeton, A. S. and Caro, T. A.: The Rock-Hosted Biosphere, Annu. Rev. Earth Planet. Sci., 51, 493–519, https://doi.org/10.1146/annurev-earth-031920-081957, 2023.

Uno, M., Koyanagawa, K., Kasahara, H., Okamoto, A., and Tsuchiya, N.: Volatile-consuming reactions fracture rocks and self-accelerate fluid flow in the lithosphere, P. Natl. Acad. Sci. USA, 119, e2110776118, https://doi.org/10.1073/pnas.2110776118, 2022.

van Wyk de Vries, B. and Merle, O.: The effect of volcanic constructs on rift fault patterns, Geology, 24, 643–646, https://doi.org/10.1130/0091-7613(1996)024<0643:TEOVCO>2.3.CO;2, 1996.

Villamor, B. P., Litchfield, N. J., Gómez-Ortiz, D., Martin-González, F., Alloway, B. V, Berryman, K. R., Clark, K. J., Ries, W. F., Howell, A., and Ansell, I. A.: Fault ruptures triggered by large rhyolitic eruptions at the boundary between tectonic and magmatic rift segments: The Manawahe Fault, Taupō Rift, New Zealand, J. Volcanol. Geoth. Res., 427, 107478, https://doi.org/10.1016/j.jvolgeores.2022.107478, 2022.

Villamor, P., Berryman, K. R., Nairn, I. A., Wilson, K., Litchfield, N., and Ries, W.: Associations between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults, Taupo rift, New Zealand: Insights into the nature of volcano-tectonic interactions, GSA Bull., 123, 1383–1405, https://doi.org/10.1130/B30184.1, 2011.

Villamor, P., Berryman, K. R., Ellis, S. M., Schreurs, G., Wallace, L. M., Leonard, G. S., Langridge, R. M., and Ries, W. F.: Rapid Evolution of Subduction-Related Continental Intraarc Rifts: The Taupo Rift, New Zealand, Tectonics, 36, 2250–2272, https://doi.org/10.1002/2017TC004715, 2017a.

Villamor, P., Nicol, A., Seebeck, H., Townsend, D., Massiot, C., McNamara, D., Ries, W., Rowland, J., Milicich, S., and Alcaraz, S.: Tectonic structure and permeability in the Taupō rift: New insights from analysis of LIDAR derived DEMs, in: Proceedings 39th New Zealand Geothermal Workshop, 22–24 November 2017, Rotorua, New Zealand, University of Auckland, New Zealand, https://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2017/025_Villamor-Final_.pdf (last access: 18 March 2024), 2017b.

Walter, T. R. and Amelung, F.: Volcanic eruptions following $M \geq 9$ megathrust earthquakes: Implications for the Sumatra-Andaman volcanoes, Geology, 35, 539–542, https://doi.org/10.1130/G23429A.1, 2007.

Wankel, S. D., Germanovich, L. N., Lilley, M. D., Genc, G., DiPerna, C. J., Bradley, A. S., Olson, E. J., and Girguis, P. R.: Influence of subsurface biosphere on geochemical fluxes from diffuse hydrothermal fluids, Nat. Geosci., 4, 461–468, https://doi.org/10.1038/ngeo1183, 2011.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR Guiding Principles for scientific data management and stewardship, Sci. Data, 3, 160018, https://doi.org/10.1038/sdata.2016.18, 2016.

Wilson, C. J. N. and Rowland, J. V.: The volcanic, magmatic and tectonic setting of the Taupo Volcanic Zone, New Zealand, reviewed from a geothermal perspective, Geothermics, 59, 168–187, https://doi.org/10.1016/j.geothermics.2015.06.013, 2016.

Wilson, C. J. N., Houghton, B. F., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., and Briggs, R. M.: Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review, J. Volcanol. Geoth. Res., 68, 1–28, https://doi.org/10.1016/0377-0273(95)00006-G, 1995.

Wilson, C. J., Gravley, D. M., Leonard, G. S., and Rowland, J. V.: Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls, Studies in volcanology: the legacy of George Walker, Special Publications of IAVCEI, 2, 225–247, 2009.

Wilson, C. J. N., Cooper, G. F., Chamberlain, K. J., Barker, S. J., Myers, M. L., Illsley-Kemp, F., and Farrell, J.: No single model for supersized eruptions and their magma bodies, Nat. Rev. Earth Environ., 2, 610–627, https://doi.org/10.1038/s43017-021-00191-7, 2021.

Wyering, L. D., Villeneuve, M. C., Wallis, I. C., Siratovich, P., Kennedy, B. M., Gravley, D. M., and Cant, J. L.: Mechanical and physical properties of hydrothermally altered rocks, Taupo Volcanic Zone, New Zealand, J. Volcanol. Geoth. Res., 288, 76–93, https://doi.org/10.1016/j.jvolgeores.2014.10.008, 2014.

Yang, T. H. J., Chambefort, I., Mazot, A., Rowe, M. C., Scott, B., Macdonald, N., Werner, C., Fischer, T. P., and de Ronde, C. E.: Understanding caldera degassing from a detailed investigation at Lake Rotoiti, Okataina Volcanic Centre, New Zealand, J. Volcanol. Geoth. Res., 433, 107716, https://doi.org/10.1016/j.jvolgeores.2022.107716, 2023.

Zhan, Y. and Gregg, P. M.: How accurately can we model magma reservoir failure with uncertainties in host rock rheology?. J. Geophys. Res.-Sol. Ea., 124, 8030–8042, https://doi.org/10.1029/2019JB018178, 2019.

Zucchi, M., Brogi, A., Liotta, D., Rimondi, V., Ruggieri, G., Montegrossi, G., Caggianelli, A., and Dini, A.: Permeability and hydraulic conductivity of faulted micaschist in the eastern Elba Island exhumed geothermal system (Tyrrhenian sea, Italy): insights from Cala Stagnone, Geothermics, 70, 125–145, https://doi.org/10.1016/j.geothermics.2017.05.007, 2017.

Sci. Dril., 33, 89–92, 2024
https://doi.org/10.5194/sd-33-89-2024
© Author(s) 2024. This work is distributed under
the Creative Commons Attribution 4.0 License.

Scientific Drilling
Open Access

The International Ocean Drilling Programme (IODP^3)

Gilbert Camoin[1], Nobu Eguchi[2], and the IODP[3] Planning Group[+]

[1]ECORD Managing Agency, Centre National de la Recherche Scientifique (CNRS), CEREGE, Europôle Méditerranéen de l'Arbois, BP80, 13545 Aix-en-Provence CEDEX 4, France

[2]Institute for Marine Earth Exploration and Engineering (MarE3), Japan Agency for Marine–Earth Science and Technology (JAMSTEC), Yokosuka, Japan

[+]A full list of authors appears at the end of the paper.

Correspondence: Gilbert Camoin (camoin@cerege.fr) and Nobu Eguchi (neguchi@jamstec.go.jp)

Published: 2 April 2024

1 Importance and history of subseafloor scientific investigation

Science-based knowledge of Planet Earth is of fundamental importance for supporting a modern resilient society facing the global challenges posed by climate change, natural hazards, energetic transition, and the needs of a safe and sustainable blue economy.

The equilibrium between Earth, human society, and ecosystems can only be achieved by considering Earth to be a system in which the understanding of Earth's history, Earth's dynamics, and the deep Earth biosphere concur with the shaping of a better future for the planet.

Scientific drilling has supported science-based knowledge of Earth's interior since the 1960s through a continued and coordinated series of international programs that together represent the largest and longest-living initiative of international scientific collaboration in the field of Earth science.

In the ocean realm, which represents about 70 % of Earth's surface, scientific drilling facilities with engineers, technicians, scientists, and managers have allowed the scientific community to access some of Earth's most challenging environments, collecting data and samples of sediments, rocks, geo-fluids, living organisms, and monitoring data from below the seafloor.

Scientific ocean drilling programs have operated for more than 5 decades: the Deep-Sea Drilling Project (DSDP) 1968–1983, the Ocean Drilling Program (ODP) 1985–2003, the Integrated Ocean Drilling Program (IODP) 2003–2013, and the International Ocean Discovery Program (IODP) 2013–2024. Scientific ocean drilling expeditions have transformed the understanding of our planet by addressing some of the most fundamental questions about Earth's evolution, narrowing knowledge gaps and generating new questions and challenges. Technological innovation by scientists and engineers has improved sampling and in situ measurement and/or monitoring tools that are now widely employed in the geosciences in both the academic and industrial sectors. Long-term borehole observatories have provided data and samples from below the seafloor. Those instruments were built by the generation of knowledge accumulated by researchers and engineers. Some of the observatories are connected to the seafloor cable network and provide in situ data in real time. Equally importantly, scientific ocean drilling has fostered enduring international collaboration, trained new generations of students and scientists across scientific disciplines, and engaged the public worldwide in scientific discoveries.

Each of the scientific ocean drilling programs has been scientifically inspired by science steering documents conceived by the international scientific community. The most recent one was published in 2020, is entitled *Exploring Earth by Scientific Drilling – 2050 Science Framework* (https://www.iodp.org/iodp-future/2050-science-framework, last access: 19 March 2024), and is envisioned through long-term, multidisciplinary research efforts that require multiple expeditions over 10- to 20-year time intervals, each combining research goals from multiple strategic objectives – the Flagship Initiatives. The 2050 Science Framework was built on the legacy of previous programs and defined seven Strategic Objectives. It also introduced "Enabling Elements" for the first time in the history of scientific ocean drilling programs. These elements aim to increase the impact of scientific and outreach initiatives, promoting partnerships and collaborations with organizations that have complementary scientific goals, e.g., land-to-sea scientific drilling in partnership with the International Continental Scientific Drilling

Program (ICDP) and stimulating continued technology development and innovative applications of advanced big data analytics.

2 Principles of the International Ocean Drilling Programme – IODP^3

The end of the International Ocean Discovery Programme on 30 September 2024 will mark major changes in the organization of international activities related to scientific ocean drilling. After decades of unified international programs, from the DSDP to the current IODP, post 2024, scientific ocean drilling initiatives will see a transition from a single international program operated by independent platform providers to independent ocean drilling programs.

The European Consortium for Ocean Research Drilling (ECORD) and Japan, who have advocated for the continuation of a single international program, intend to continue providing scientific ocean drilling opportunities post 2024 to the international scientific community, based on their well-established infrastructures, competitiveness in the international research landscape, and maximum scientific return from investment.

Through a 2-year long process of exchange of views and ambitions, ECORD and Japan agreed to build a joint scientific ocean drilling program: the IODP^3 (IODP-cubed).

The IODP^3 will consist of an international scientific collaboration addressing important questions in the Earth, ocean, environmental, and life sciences described in the 2050 Science Framework, based on the study of rock and/or sediment cores, borehole imaging, in situ observatory data, and related geophysical imaging obtained from the subseafloor.

The IODP^3 will adopt a transparent, open, flexible, and international modus operandi, program-wide standard policies and guidelines, sustainable management, and publicly accessible knowledge-based resources. The IODP^3 will adopt the 2050 Science Framework Enduring Principles.

3 Objectives and organization of the IODP^3

IODP^3 investigations will be based on research proposals that address the objectives of the 2050 Science Framework or other outstanding new research ideas.

The IODP^3 will implement and fund

- offshore expeditions following an expanded Mission Specific Platform (MSP) concept and
- Scientific Projects using Ocean Drilling ARChives (SPARCs) that are international and multidisciplinary projects with objectives originating from or based on ocean drilling archives.

Drilling and SPARC proposals will be submitted with a bottom-up process to the IODP^3 Science Office by teams of proponents belonging to the international research community.

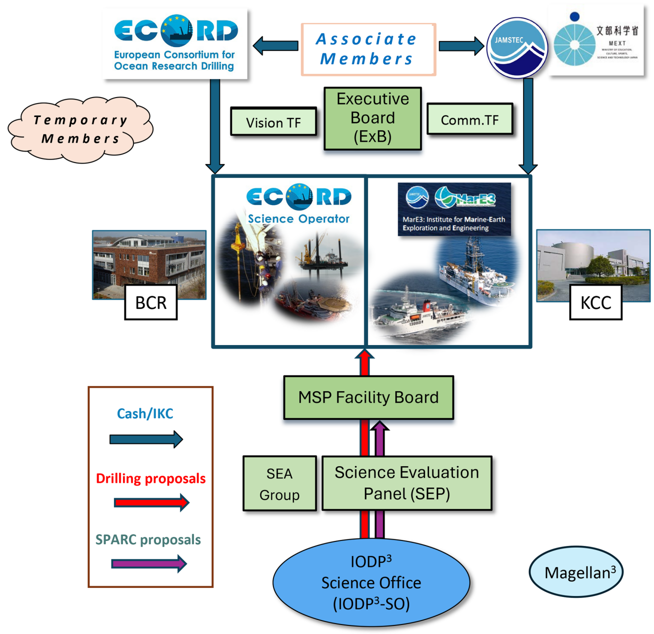


Figure 1. Organization of the International Ocean Drilling Programme. Photos and logos: © ECORD/IODP, © JAMSTEC, and © JAMSTEC/KCC.

The primary responsibility of the Science Evaluation Panel (SEP; Fig. 1) is to evaluate all proposals submitted to the IODP^3 in a fair, open, and transparent manner in terms of both scientific excellence and the completeness and quality of the site characterization data packages. The SEP will be composed of top international experts selected through competitive calls.

The Safety and Environment Advisory (SEA; Fig. 1) Group will be an advisory body to the MSP-FB, SEP, and IODP^3 Operators and will provide independent advice regarding potential safety and environmental issues associated with the general and specific geological settings of proposed IODP^3 drill sites.

The SEP and the SEA Group will be logistically supported by the IODP^3 Science Office and will serve all the platforms employed by the program. IODP^3 drilling expeditions and SPARCs will be scheduled by the MSP Facility Board based on their scientific merit and operational constraints within the limits of the available resources.

The IODP^3 Executive Board (ExB; Fig. 1) will be the IODP^3 entity responsible for ensuring effective decision-making and overseeing the program.

The Magellan^3 Workshops will be designed to support scientists from IODP^3 and ICDP members in developing new and innovative scientific drilling proposals that meet the ambitions of the 2050 Science Framework and/or the ICDP Science Plan 2020–2030 by funding or co-funding workshop proposals and travel grants.

The $IODP^3$ will include two task forces (Fig. 1): the Vision Task Force will be in charge of developing a long-term scientific and funding strategy, and the Communication Task Force will be in charge of program-wide communication activities.

3.1 MSP expeditions

$IODP^3$ drilling expeditions will be implemented by the MSP Operators, ESO and/or JAMSTEC-MarE3, following the MSP concept. This concept will be an expanded MSP concept by diversifying drilling and coring technologies – riserless and riser drilling, giant piston coring – and applying them to all drilling environments, as determined by scientific priorities, operational efficiency, and better value for money. D/V *Chikyu* and R/V *Kaimei* are identified as MSP facilities that are crucial facilities for the successful implementation of the 2050 Science Framework.

Land-to-Sea Transects (L2S), requiring scientific drilling at both onshore and offshore sites or at shallow marine sites to be implemented jointly with the ICDP, are one of the prime objectives of the $IODP^3$.

The duration of $IODP^3$ expeditions will be flexible and determined by scientific requirements and available funds.

$IODP^3$ drilling expeditions will be scheduled by the MSP Facility Board based on their scientific merit and operational constraints within the limits of the available resources.

$IODP^3$ expeditions are intended to have no significant environmental impact, and they are carried out in conformance with the highest accepted levels of environmental sensitivity.

$IODP^3$ expeditions will be undertaken by international teams of scientists – Science Parties – selected by the MSP Operator(s) and Co-chief Scientists and based on recommendations made by Program Member Offices (PMOs). Staffing decisions will consider, as far as possible, the goal of achieving the maximum diversity of gender, career stage, nationality, discipline, and culture in the Science Parties.

The sizes of the expedition Science Parties will be flexible and determined by scientific requirements.

The $IODP^3$ will include the services provided by the current IODP core repositories in Bremen (BCR) and Kochi (KCC).

The $IODP^3$ will provide open access to all expedition samples and data once the expedition Science Party members have had the opportunity to complete the initial studies within the established moratorium period, typically 1 year. After the expiration of the moratorium period, the program will make samples, cores, and data available to any scientist, in accordance with the $IODP^3$ Samples, Data and Obligations Policy following findability, accessibility, interoperability, and reusability (FAIR) data principles.

3.2 SPARCs

The $IODP^3$ SPARCs provide a mechanism for the international scientific ocean drilling community to propose new large-scale projects that may address any aspect of the 2050 Science Framework and involve interdisciplinary collaborations.

SPARCs will have objectives that maximize the return on the legacy assets (i.e., cores, samples, and data from current and past scientific ocean drilling programs) without new drilling or other operations at sea.

SPARCs will address globally significant processes and problems and use innovative, creative, and multidisciplinary approaches that could include, for example, the production of large new datasets from samples, integration of data across multiple expeditions and/or multiple boreholes, and/or the application of new methods or technologies (e.g., AI, "big data" approaches) that were not available when the legacy assets were collected. The scientific ambition of SPARC projects should far exceed that of standard requests for samples or data as they are intended to provide a new avenue to facilitate collaboration at scales larger than conventional single- or multi-proponent sample requests. In parallel, standard requests for samples and data may be submitted at any time.

Each SPARC will have a funded duration of 3 years and will receive EUR 300 000 for its implementation. SPARC proposals should have a maximum of five co-proponents. All the co-proponents of a funded SPARC will automatically become Science Party members (with two selected as Co-Chief Scientists), but the remaining Science Party members will be selected following an open call for applications. The overall size of the final Science Party for a SPARC is flexible and can be adapted to project needs but will normally consist of a minimum of 15 scientists, with no fixed upper limit.

4 $IODP^3$ partnership

As Platform Providers, ECORD and Japan will be the $IODP^3$ Core Members.

International governmental and non-governmental entities not regularly providing scientific ocean drilling platform(s) to the $IODP^3$ can become Associate Members by making annual cash contributions to the $IODP^3$ (on the order of EUR 1 million) or as Temporary Members by providing cash and/or project-based in-kind contributions (IKCs) (with a minimum of EUR 0.5 million) to access $IODP^3$ expedition(s). The Australian and New Zealand IODP Consortium (ANZIC) and India have already sent letters of interest to become $IODP^3$ Associate Members.

IKC and/or cash contributions from any $IODP^3$ member or non-member country or institution are potentially acceptable for funding offshore expeditions. IKCs may include essential scientific or operational services that the $IODP^3$ would normally pay for, fully or partly funded drilling platforms, support vessels, hazard site surveys (if required), permission assistance, onshore facilities near drill sites (if required), ice management, and remote logistical assistance.

IODP^3 will set up an overarching Scientific Drilling Forum as a venue for exchanging ideas, views, and information between all international research programs that employ scientific drilling to explore Earth and planetary processes.

5 Forward look

Based on the well-established operation of the ECORD and JAMSTEC infrastructures, their successful implementation, their competitiveness in the international research landscape and a maximum return from investment, a bright future is promised to the international communities and ECORD and Japan in their intentions to play a prominent role in post-2024 scientific ocean drilling.

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

Team list. IODP^3 Planning Group: Gilbert Camoin (EMA, ECORD Managing Agency/CEREGE, Aix-en-Provence, France), Nobu Eguchi (MarE3, Institute for Marine-Earth Exploration/-JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Angelo Camerlenghi (ESSAC, ECORD Science Support and Advisory Committee/National Institute of Oceanography and Applied Geophysics, Trieste, Italy), Nadine Hallmann (EMA, ECORD Managing Agency/CEREGE Aix-en-Provence, France), Annalisa Iadanza (ECORD Council/Consiglio Nazionale delle Ricerche, Rome, Italy), Minoru Ikehara (J-DESC, Japan Drilling Earth Science Consortium/Kochi University, Japan), Fumio Inagaki (MarE3, Institute for Marine-Earth Exploration/-JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Katsuyoshi Kawaguchi (MarE3, Institute for Marine-Earth Exploration/JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Masataka Kinoshita (Japan Drilling Earth Science Consortium/University of Tokyo, Japan), Yusuke Kubo (KCC, Kochi Core Center/JAMSTEC, Japan Agency for Marine-Earth Science and Technology/Kochi, Japan), Shin'ichi Kuramoto (JAMSTEC, Japan Agency for Marine-Earth Science and Technology/Yokosuka, Japan), France Lagroix (ECORD Council/Institut du Globe de Paris, France), Guido Lu¨niger (ECORD Council/German Research Foundation, Bonn, Germany), Harue Masuda (J-DESC, Japan Drilling Earth Science Consortium/Osaka Metropolitan University), Dave McInroy (ESO, ECORD Science Operator/British Geological Survey, Edinburgh, UK), Tomo Morishita (J-DESC, Japan Drilling Earth Science Consortium/Kanazawa University, Japan), Yuki Morono (J-DESC, Japan Drilling Earth Science Consortium/KCC, Kochi Core Center/JAMSTEC/Kochi, Japan), Tony Morris (ECORD Science Support and Advisory Committee, Univ. Plymouth, UK), Natsumi Okutsu (MarE3, Institute for Marine-Earth Exploration/JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Sanny Saito (J-DESC, Japan Drilling Earth Science Consortium/MarE3, Institute for Marine-Earth Exploration/-JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Nobukazu Seama (CIB, Chikyu IODP Board/Kobe University, Japan), Ursula Röhl (ESO, ECORD Science Operator/BCR, Bremen Core Repository, Germany), Hiroyuki Tojo (MarE3, Institute for Marine-Earth Exploration/JAMSTEC, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan), Gen Totani (MEXT, Ministry of Education, Culture, Sports, Science and Technology/Ocean and Earth Division, Tokyo, Japan), Sasha Turchyn (EFB, ECORD Facility Board/Cambridge University, UK), Gabriele Uenzelmann-Neben (EFB, ECORD Facility Board/Alfred Wegener Institute, Bremerhaven, Germany), and Mike Webb (ECORD Council/Natural Environment Research Council, Swindon, UK).

Author contributions. All the authors have collaborated in the development of the concepts described in this paper, as well as the preparation, creation, and/or presentation of the published work. GC and NE have conceived the summary of the paper and have synthesized and written all parts of the paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

ECORD School of Rock and ECORD-sphere exhibition in Naples, Italy

Angelo Camerlenghi and Hanno Kinkel, ESSAC Office, OGS, Trieste

In the occasion of the port Call of the JOIDES Resolution in Naples (February 9-14, 2024) before Expedition 402 - Tyrrhenian Continent–Ocean Transition, several events where organized, including the ECORD School of Rock "Understand the Planet through ocean exploration" (Naples 9-11 2024). The ECORD School of Rock is a workshop designed by scientists and outreach/education officers who have sailed onboard IODP/ODP expeditions to share their at-sea experience with teachers of their home country and to introduce educational resources which can be used in the classroom. The teachers thus experience an immersive research experience: "With scientists as scientists".
The ECORD School of Rock "Understand the Planet through ocean exploration" was promoted and organized by Prof. Claudia Lupi (university of Pavia) and Prof. Ester Piegari (University of Naples Federico II) within the activities of IODP-Italia, and was attended by forty science teachers from all over Italy. Through lectures alternating with practical activities the participants discovered the scientific drilling tools of the International Ocean Discovery Program for unravelling the Earth secrets. The seminar lessons took place in the Royal Mineralogical Museum and the Paleontological Museum, while the practical activities were held in the laboratories of the Department of Earth, Environment and Resources Sciences at the University of Naples Federico II. All participants had the unique opportunity to visit the JOIDES Resolution with a guided tour by experts and to meet the scientists who will take part in the upcoming JOIDES expeditions.
As part of the program, the participants visited the temporary exhibition on scientific drilling hosted by the Paleontological Museum, featuring the ECORD-Sphere.

Annalisa Iadanza (CNR, IODP Italy) illustrates scientific ocean drilling to the School of Rock participants in front of the ECORD Sphere.

On our own behalf:

In the past, it has happened that articles ready for publication in SCIENTIFIC DRILLING were published after waiting for weeks or even months. This was due to technical reasons, as all Scientific Reports pending publication in a volume first had to be assigned a doi before this could be done for Workshop Reports, Technical Developments and Progress Reports.
To avoid these problems in the future, we will adapt our publication concept with the next issue of SCIENTIFIC DRILLING and switch to a full online journal where articles will be released promtly as soon as they are ready for publication and without delay. Volumes are only published online and no longer provided in printed form. We hope that this alignment with modern realities will attract even more authors and readers in the future.

Schedules

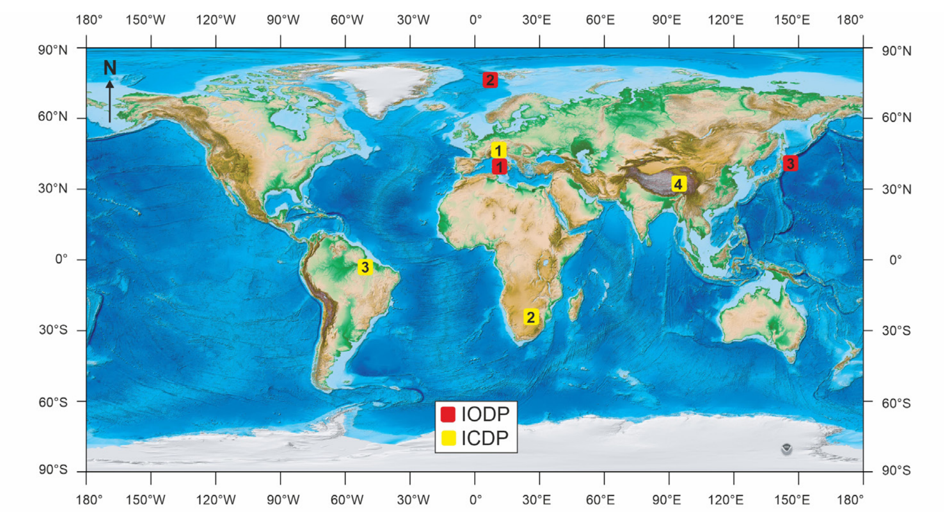
IODP – Expedition schedule http://www.iodp.org/expeditions/

USIO operations	Platform	Dates	Port of origin
1 Tyrrhenian Continent-Ocean Transition (Exp 402)	JOIDES Resolution	Feb 9–Apr 8, 2024	Napoli
2 Eastern Fram Strait Paleo-archive (403)	JOIDES Resolution	Jun 4–Aug 2, 2024	Amsterdam
3 Japan Trench Tsunamigenesis (405)	Chikyu	Sep 12–Dec 20, 2024	Shimizu

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

ICDP project	Drilling dates	Location
1 Drilling the Ivrea-Verbano ZonE (DIVE)	Dec 2023–Apr 2024	Northern Italy (Megolo))
2 Bushveld Drilling Project (BVDP)	Mar 2024–Feb 2025	South Africa (Mpumalanga, Limpopo)
3 Trans-Amazon Drilling Project (TADP)	May–Sep 2024	Brazil (Pará)
4 Nam Co Drilling Project (NamCore)	Jun–Aug 2024	Lake Nam Co, Tibetian Plateau

Locations



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