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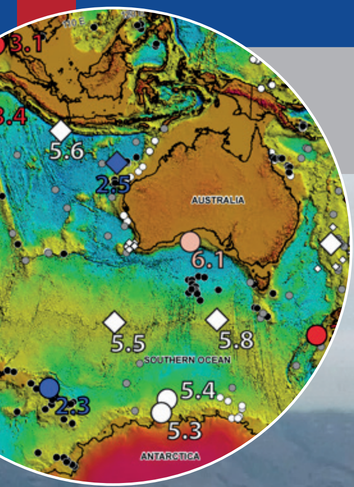
Reports on Deep Earth Sampling and Monitoring



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Dear Reader,

This issue of the journal Scientific Drilling surveys how far in time current research on the paleoenvironment is going to look back and how many different approaches as well as different locations are taken to decipher the workings of our planet. It also provides information on dramatic cataclysmic events that not only shape the Earth´s surface but that also eclipse the time for revolutionary changes in life.
The Colorado Plateau in western North America consists of Palezoic to Mesozoic mainly fluvial sediments that have been retrieved within the Colorado Plateau Coring Project to shed new light in high resolution on paleoenvironmental changes and possible bolide impact events such as the Manicouagan Event that followed shortly after the End-Permian Extinction (**p. 15**).
The evolution of our hominid ancestors since the late Miocene is preserved in great richness in the Chad Basin in tropical northern Africa. The sediments deposited in continuous lacustrine systems preceding the present Lake Chad contain critical information on a 600 000 km^2 watershed evolution driven by orbital forcings (**p. 71**).
On the other side of the globe, a lake drilling endeavour in New Zealand was able to core youngest post-glacial sediments to study variability of extreme and flood events over the past 17 000 years with up to annual resolution; see **p. 41**.
However, the Southern Hemisphere's land coverage is small, so climate and environmental archives of the past lay mostly in the southern oceans. Their sediment records have by far not been studied to an extent comparable to those of the north. Accordingly, critical research targets of the eastern Indian and southwestern Pacific oceans have been discussed in a workshop to prioritize goals of future marine expeditions (**p. 61**). Data from previous IODP and ODP expeditions have been reviewed during a workshop in China (**p. 87**) in the context of variability of the monsoon system on a global scale to go beyond regional-scale studies.
Natural disaster research topics were addressed in a meeting on existing core, log, and seismic data from previous IODP expeditions in the Nankai Trough (NanTroSEIZE) in Japan (**p. 93**) to shed light on the role of the deformation front in tsunamigenic earthquakes and slow slip in the shallow portion of the subduction interface. Furthermore, high-quality downhole logs and borehole imaging data were acquired during IODP–ICDP Expedition 364 to the Chicxulub impact crater (**p. 1**) and utilized to differentiate geological from operation-related features, which is critical for downhole logging-data quality control and interpretation.
Renewable energy research on the Newberry Volcano in Oregon as one of the largest geothermal heat reservoirs in the USA has been conducted for 40 years. However, now a workshop has discussed how to reach through a deep hole to the ductile–brittle transition zone (T>400 C) at Newberry Volcano, to set a new and ambitious goal for a future ICDP project (**p. 79**).
And last but not least, Earth and life scientists are facing new legislative challenges through the Nagoya Protocol of the Convention on Biological Diversity. A paper (**p. 51**) summarizes the central points of the Nagoya Protocol on access and benefit-sharing in relation to ocean drilling research in complying with this international convention.

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

Aims & scope

Scientific Drilling (SD) is a multidisciplinary journal focused on bringing the latest science and news from the scientific drilling and related programmes to the geosciences community. Scientific Drilling delivers peer-reviewed science reports from recently completed and ongoing international scientific drilling projects. The journal also includes reports on engineering developments, technical developments, workshops, progress reports, and news and updates from the community.

Editorial board

Additional information

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Cover figure: Drilling at Lake Ohau, South Island, New Zealand, using a purpose-built barge and drilling system. Photograph by Richard Levy.
Insert 1: Potential sites for future IODP drilling in the southern Indian and southwestern Pacific oceans.
Insert 2: Fishermen on Lake Chad in the Sahel/Sahara region of central northern Africa. Photograph by Florence Sylvestre.

Call for abstracts to IODP-ICDP sessions at EGU 2019

SSP1.2/CL/EMRP3.11/GD2.9/GMPV1.7/NH5.12/TS – Achievements and perspectives in scientific ocean and continental drilling (co-sponsored by JpGU)
https://meetingorganizer.copernicus.org/EGU2019/session/31032
EOS4.2 – Outreach in geoscience: What does it mean to you?
https://meetingorganizer.copernicus.org/EGU2019/session/31743

Deadline for abstract submission:
10 January 2019

Framing a successor programme to IODP

ECORD organizes a 2-day workshop directed at initiating concepts and defining new goals for a future international scientific ocean drilling programme to be developed beyond 2023. Special emphasis will be on new science frontiers and technological developments in a multiple drilling platform approach.

The workshop is entitled **PROCEED** – *EX***P***ANDING F***RO***NTIERS OF S***C***I***E***NTIFIC OC***E***AN* **D***RILLING*, and will be held at the Austrian Academy of Sciences (ÖAW), Vienna (Austria), on **6–7 April 2019**, right before EGU 2019.

The objective of the PROCEED workshop is to produce a **White Paper**, which will summarize the scientific, technological, and programmatic goals for ECORD beyond 2023. This document will constitute the foundation for interactions with our IODP partners, who will also start to get organized in 2019 at their national/consortium level. The coordination of all these actions to build a new programme is still to be defined.

If you want to attend the PROCEED workshop and take part in the building of the future of ECORD and IODP, register by email to ema@cerege.fr before 17 February 2019.
http://www.ecord.org/science/proceed/

ECORD/ICDP MagellanPlus Workshop Series Programme – Call for Proposals

The **ECORD/ICDP MagellanPlus Workshop Series Programme** invites proposals to organize workshops to support the development of IODP/ICDP proposals.

MagellanPlus would particularly welcome proposals for workshops that integrate scientific marine and continental coring with scientific topics such as Earth's Surface Environmental Change, Processes and Effects; the Deep Biosphere & Sub-Seafloor Ocean; as well as Solid Earth Cycles & Geodynamics, as outlined in the science plans of IODP and ICDP.

The contribution of the MagellanPlus Workshop Series will not exceed 15000 Euros per workshop. Proponents are encouraged to seek co-funding from other sources. Workshops will be held no later than 12 months after approval by the MagellanPlus Science Steering Committee.

Proposals must include the following.
1) Short summary (max. 500 characters) stating the purpose of the proposed workshop, its location and expected impact;
2) Full description (max. 2 pages) of the proposed workshop outlining the purpose, rationale, expected impact and number of participants;
3) Preliminary workshop programme;
4) List of keynote speakers;
5) Full budget for the workshop;
6) CV (max. 1 page) plus a list of international, peer-reviewed publications for the last 5 years, of the main applicant.

Proposals must be submitted as a single, combined pdf document and email attachment to **magellan.plus@uu.nl** and to **ema@cerege.fr**.

The deadline for applications is 15 January 2019.

For further information, please contact **magellan.plus@uu.nl**.
http://www.ecord.org/science/magellanplus

New ICDP Chair Marco Bohnhoff

The ICDP Executive Committee and Assembly of Governors have appointed Marco Bohnhoff as the chair of the Executive Committee. Marco Bohnhoff is Professor for Experimental and Borehole Seismology at the Free University Berlin and head of the Geomechanics and Rheology section at the GFZ German Research Centre for Geosciences. He has extensive knowledge in the field of scientific drilling and brings ICDP experience through his role as Principal Investigator in various ICDP projects, including the Geophysical borehole Observatory at the North Anatolian Fault (GONAF), Deep Drilling at Koyna for Reservoir Triggered Seismicity, and a STrainmeter ARray in shallow boreholes of the northern Apennines (STAR). Marco has stated that he is far from being idealistic, but that he is a true believer that the ICDP philosophy of co-mingled international funding is the right way to go…and that ICDP is a blueprint for how to tackle ambitious challenges in a globalized multipolar world.

Petrophysics Summer School 2018

The University of Leicester played host to the third Petrophysics Summer School between 1 and 6 July 2018. The summer school initiative was started in 2016 as part of the UK's International Ocean Discovery Program (IODP) knowledge exchange fellowship. This year's school brought together 21 participants from 5 countries (by institution; 10 by nationality) from as far away as the Philippines. Over two-thirds of the 2018 cohort were women, which was a significant increase on the previous 2 years in which women made up less than half of the group. Similar to other years, the participant group comprised mainly graduate students (PhD and Masters), but also included a number of post-doctoral researchers, and an undergraduate and more senior scientists, most of whom had little or no experience with petrophysics. The 6-day course combined lectures, practicals, software training in Schlumberger's Techlog, and site visits to Weatherford and the British Geological Survey (BGS) Core Store, to provide a solid introduction to the fundamentals and applications of petrophysics. There was also an opportunity for participants to introduce themselves and present their research during a mini-conference held on the first day. The course is accredited by the Continuing Professional Development (CPD) Standards Office, meaning that participants, on completion of the course, received a formal certificate indicating receipt of 36 hours of accredited CPD.

A pool of 14 instructors from both academia (European Petrophysics Consortium (EPC, comprising the Universities of Leicester and Montpellier), Imperial College London, Lamont-Doherty Earth Observatory of Columbia University, University of Leicester) and industry (BP (UK), Schlumberger Information Systems and Total E&P UK) delivered training throughout the week, drawing on their many and varied experiences and including real-world examples from both commercial and IODP projects (notably, but not exclusively, Expedition 346 Asian Monsoon).

The third Petrophysics Summer School was made possible via funding from the UK IODP (funded via the Natural Environment Research Council (NERC)), European Consortium for Ocean Research Drilling (ECORD) and London Petrophysical Society (LPS). Significant in-kind contributions were also made by EPC, Weatherford (Reeves Wireline Services, East Leake), and the BGS Core Store. Over half of the participants' attendance was supported via generous scholarships/bursaries from the United States Science Support Office (USSSP, 10 bursaries) and ECORD (1 scholarship).
It is anticipated that a fourth Petrophysics Summer School may be held in 2019 – further information will be available in January 2019 via www.le.ac.uk/epc.

Schedules

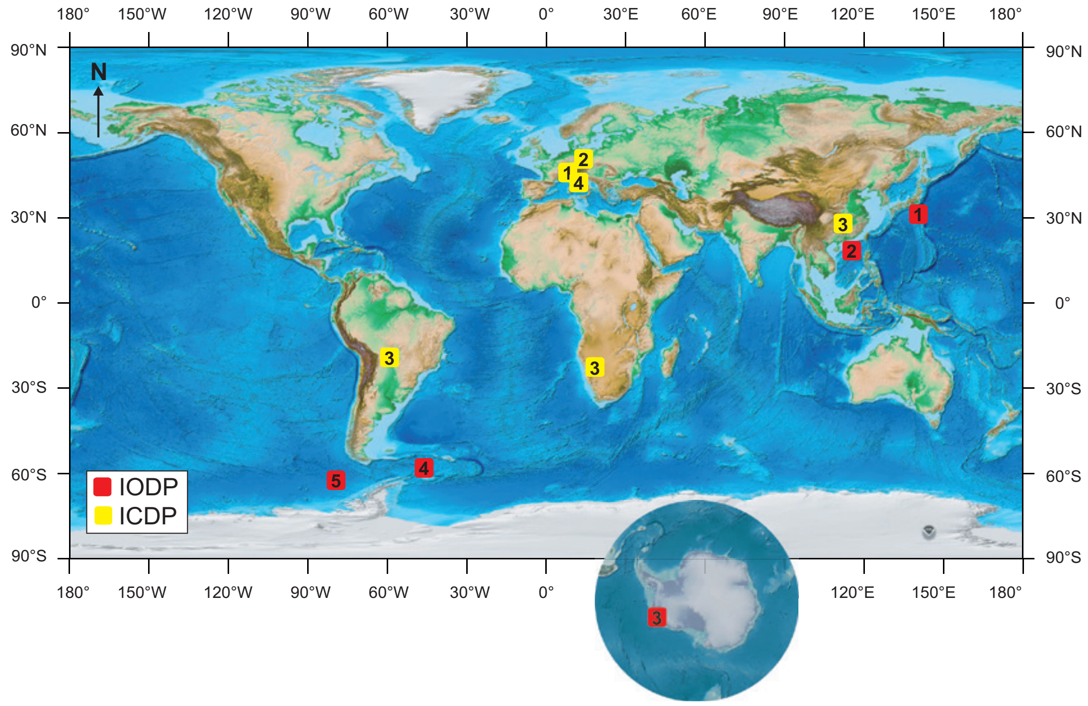
IODP – expedition schedule http://www.iodp.org/expeditions/

CDEX operations	Platform	Dates	Port of origin
1 Exp 358 (NanTroSEIZE): Plate Boundary Deep Riser 4	Chikyu	Oct 7, 2019–Mar 21, 2019	Shimizu
USIO operations	**Platform**	**Dates**	**Port of origin**
2 Exp 368X: Return to Hole U1503A (South Chica Sea) – *tentative*	JOIDES Resolution	Nov 15–Dec 8, 2018	Hong Kong
3 Exp 379: Amundsen Sea West Antarctic Ice Sheet History	JOIDES Resolution	Jan 18–Mar 20, 2019	Punta Arenas
4 Exp 382: Iceberg Alley & Subantarctic Ice and Ocean Dynamics	JOIDES Resolution	Mar 20–May 20, 2019	Punta Arenas
5 Exp 383: Dynamics of Pacific Antarctic Circumpolar Current	JOIDES Resolution	May 20–July 20, 2019	Punta Arenas

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

ICDP project	Drilling dates	Location
1 DOVE	May 2019–Oct 2019	Alps
2 Eger Rift	Nov 2018–June 2019	West Bohemia, Czech Republic
3 GRIND	Mar 2019–Aug 2019	Namibia, Brazil, China
4 STAR	May 2019	Northern Apennines, Italy

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).

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Scientific Drilling
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Science Reports

Drilling-induced and logging-related features illustrated from IODP–ICDP Expedition 364 downhole logs and borehole imaging tools

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Abstract. Expedition 364 was a joint IODP and ICDP mission-specific platform (MSP) expedition to explore the Chicxulub impact crater buried below the surface of the Yucatán continental shelf seafloor. In April and May 2016, this expedition drilled a single borehole at Site M0077 into the crater's peak ring. Excellent quality cores were recovered from ~ 505 to ~ 1335 m below seafloor (m b.s.f.), and high-resolution open hole logs were acquired between the surface and total drill depth. Downhole logs are used to image the borehole wall, measure the physical properties of rocks that surround the borehole, and assess borehole quality during drilling and coring operations. When making geological interpretations of downhole logs, it is essential to be able to distinguish between features that are geological and those that are operation-related. During Expedition 364 some drilling-induced and logging-related features were observed and include the following: effects caused by the presence of casing and metal debris in the hole, logging-tool eccentering, drilling-induced corkscrew shape of the hole, possible re-magnetization of low-coercivity grains within sedimentary rocks, markings on the borehole wall, and drilling-induced changes in the borehole diameter and trajectory.

1 Introduction

Expedition 364 was a joint International Ocean Discovery Program (IODP) and International Continental Scientific Drilling Program (ICDP) Mission Specific Platform (MSP) expedition (Morgan et al., 2017). It drilled and cored a single borehole (Hole M0077A) at a shallow water depth in the Chicxulub impact crater buried below the surface of the Yucatán continental shelf (Mexico). This crater is the best preserved of the three largest impact structures on the earth (Grieve and Therriault, 2000), has an intact, unequivocal topographic peak ring, is associated with a global ejecta layer, and has been directly linked to the K–Pg mass extinction (e.g., Schulte et al., 2010; Kring, 2007).

The post-impact sedimentary cover sequence (0–617.33 m b.s.f.) and the peak ring of the Chicxulub impact crater (617.33–1334.69 m b.s.f.) were drilled during Expedition 364 (Fig. 1c). Details on both scientific objectives and

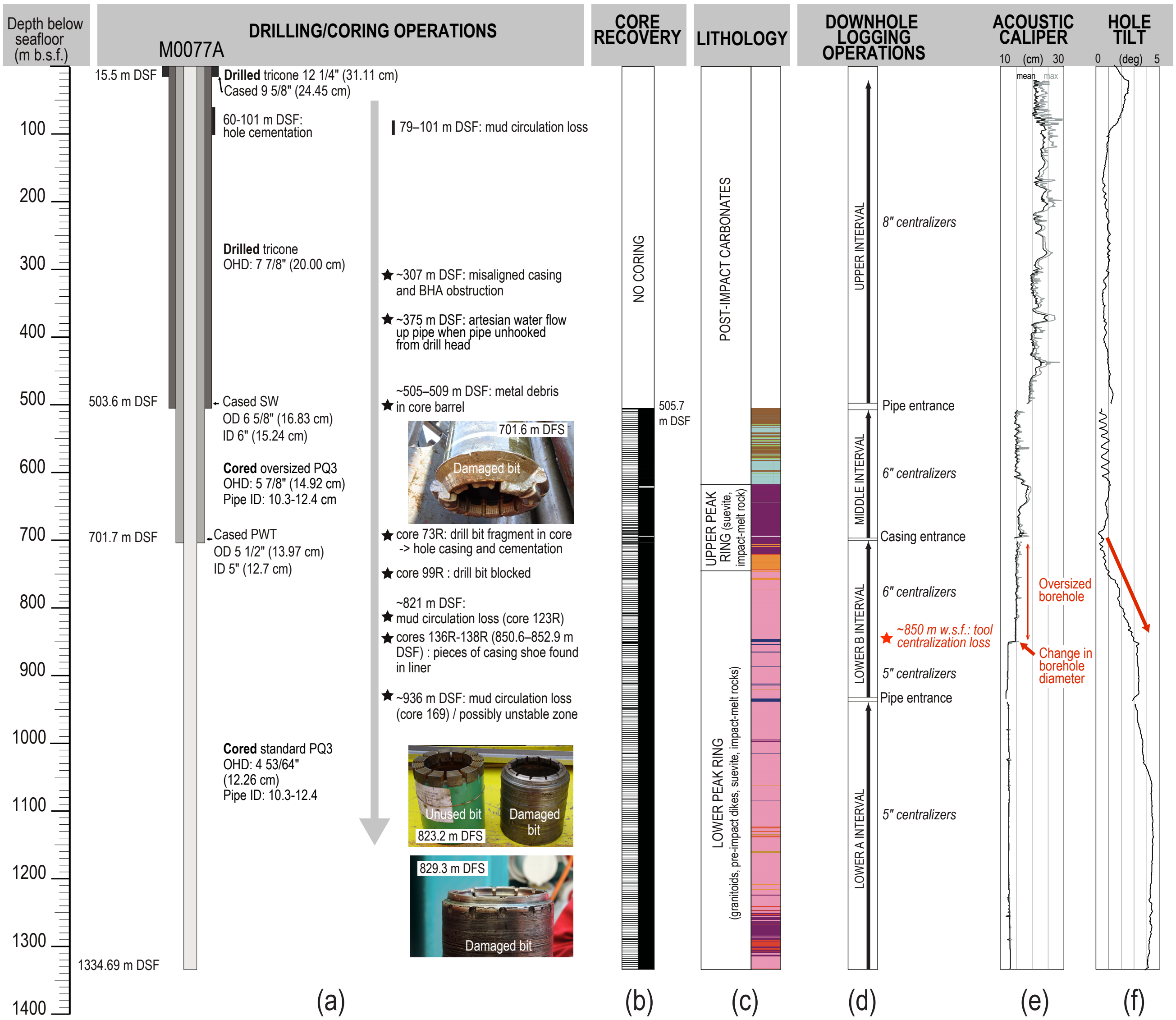

Figure 1. Summary of drilling, coring, and logging operations at Site M0077. The downhole logging data were acquired with slimline tools in three different phases (upper, middle, and lower intervals). Note the change in borehole diameter at ~ 850 m w.s.f. (wireline seafloor) preceded by an increase in the borehole tilt (see discussion in Sect. 4.3). Pictures illustrate damaged drill bits. ID is the inner diameter, OD the outer diameter, and OHD the open hole diameter; m b.s.f. is meters below seafloor and DSF is the driller's depth below seafloor.

operations can be found in the IODP proceeding volume (Morgan et al., 2017). In total, 303 cores were recovered from 505.7 to 1334.69 m b.s.f. (Fig. 1b). Open hole downhole logs were acquired with slimline tools over almost the entire depth (Fig. 1d). Due to favorable borehole conditions, the recovery and overall quality of the downhole logging data are good to excellent, with the exception of the upper ~ 400 m b.s.f. within the rotary drilled younger carbonates that exhibit karst features.

In general, downhole wireline logging tools are used to measure a suite of physical properties within the rocks surrounding the borehole as well as to image the borehole wall. These logs provide critical geological information about the rock formations close to the borehole, including their lithology, fluid content, porosity, and structural data such as the presence of faults and fractures. Where core recovery is incomplete, log data provide an invaluable way to characterize the geological formation. Where core recovery is good, log and core data are complementary and can be interpreted jointly. In addition, downhole logs measure formation properties on a scale that is intermediate between the one obtained from measurements on core samples at the laboratory and the one obtained from surface geophysical surveys. Logging is thus useful for the integration of physical properties at various scales. Downhole logs can also allow the assessment of borehole quality (e.g., hole shape and trajectory) and can provide assistance with decision support during drilling and coring operations. Differentiating between in situ natural geological features, generally also visible on cores, and drilling-induced or logging-related features is part of the data quality control process and is critical for the interpretation of well-log data. Logging-related and drilling-induced features have been described in several studies (e.g., Lofts and Bourke, 1999; Cheung, 1999); here, we provide examples from Site M0077. We focus mainly on acoustic borehole images that provide invaluable source of information for sub-surface geology characterization. We will also show how downhole logs have been used to improve the post-operation understanding of the drilling and coring operation history.

2 Expedition 364 offshore operations

As for all MSP expeditions, the downhole logging program was coordinated by the European Petrophysics Consortium (EPC), which is part of the European Consortium for Ocean Drilling (ECORD) Science Operator (ESO). MSPs employ various coring technologies and pipe sizes (here PDC Tricone, oversize PQ3, PQ3; Fig. 1a) and drill in a variety of water depths (here <20 m water depth), each of which provides technical constraints on the nature of logging operations and the set of downhole geophysical tools that can be used on a case-by-case basis. Taking into account the technical constraints, the logging program is designed to help meet the expedition-specific scientific objectives.

2.1 Overview of downhole logging operations

For Expedition 364, downhole logging operations at Site M0077 were funded by the ICDP. Slimline wireline logging services were contracted by EPC from the University of Montpellier–CNRS (France). Logged data included total gamma radiation, sonic velocity, acoustic and optical images of the borehole wall, electrical formation resistivity, induction formation conductivity, magnetic susceptibility, magnetic field azimuth and intensity, and caliper and borehole fluid parameters (Table 1). Details on logging procedure and logging-tool measurement principles can be found in Morgan et al. (2017). Additional technical schemes on individual logging tools and information can be found on the tool manufacturers' websites (http://geovista.co.uk/, last access: 12 October 2018 and https://www.alt.lu/, last access: 12 October 2018).

Logs were recorded either with stand-alone logging tools or for the first time in MSPs, with stackable ultra-slimline tools (tool diameter without centralizers: 3.8 to 5.2 cm) combined into tool strings. Most of the measurements were acquired in open borehole conditions (no casing). Hole M0077A was drilled using a series of drill strings of reducing diameters down to the base of the hole at 1334.7 m b.s.f. (Fig. 1a). The downhole logging runs were performed in stages in order to allow the hole to be cased and ensure the hole remained open and logs could be collected from the entire drilled interval. Data were acquired in three logging phases at intervals ∼ 0–503 (upper interval), ∼ 506–699 (middle interval) and ∼ 700–1334 m (lower interval) wireline seafloor (m w.s.f.; Fig. 1d). In preparation for logging, the boreholes were either flushed of debris by circulating sea water (upper and lower intervals) or left filled with drill mud (middle interval). In each interval logged, the bottom hole assembly (BHA) was either pulled up, or entirely pulled out. During each logging run, incoming data were recorded and monitored in real time with a data acquisition system. As the *L/B Myrtle* drill ship was jacked up above the sea surface, there was no ship heave and thus no need to use a wireline heave compensator.

Advanced Logic Technology (ALT)'s WellCAD software package was used for the visualization, processing, and plotting of the downhole data. The processed data are available online in the IODP database (http://mlp.ldeo.columbia.edu/logdb/scientific_ocean_drilling/, last access: 12 October 2018) along with information about how they were collected and processed. Further information can be found in Morgan et al. (2017). During the processing of the downhole logging data, both drilling-induced and logging-related features were noticed. These are described below, and should be kept in mind when making any future geological interpretations of the logging data. In addition, most of the features discussed are not specific to Expedition 364 or to slimline tools and could be observed in logging data acquired during other IODP Expeditions.

2.2 Borehole-imaging logging tools

Borehole-imaging logging tools are commonly used by both the IODP and ICDP (e.g., Lovell et al., 1998). They involve measuring either the electrical conductivity of the borehole wall (Formation MicroScanner tool, Pezard and Lovell et al., 1990; Gaillot et al., 2007; Pezard et al., 1992a, b; Ekstrom et al., 1987) or the sonic travel time and amplitude of a reflected ultrasonic pulse (acoustic borehole imager – ABI – in this study; Table 1; Zemanek et al., 1969, 1970; Zoback and Anderson, 1982; Anderson and Zoback, 1983; Hayman et al., 1998). A third category allows for the recording of an optical image of the borehole wall (optical borehole imager – OBI – in this study; Table 1; e.g., Paillet et al., 1990; Inwood et al., 2008).

During Expedition 364, both optical and acoustic borehole imagers were used. The OBI tool used has the ability to produce high-resolution optical images of the borehole wall down to a millimeter scale (https://www.alt.lu/). This logging tool incorporates a high-resolution, high-sensitivity CCD digital camera located above a conical mirror that captures the image of the borehole wall. The light source is provided by an LED ring assembly located in the optical head.

Table 1. Summary of wireline slimline probes; Expedition 364. Modified from Morgan et al. (2017).

Wireline tool	Slimline tools acronyms and full name		Manufacturer	Tool string position	Focus on	Measurement spacing interval (up logs)
Stackable	QL40-SGR	Spectral Gamma Ray Probe	ALT/Mount Sopris Instruments	In-line sub	Formation	5 cm
	QL40-FWS	Full Waveform Sonic	ALT/Mount Sopris Instruments	In-line sub	Formation	5–10 cm
	QL40-Ocean	Idronaut Ocean Seven	ALT/Mount Sopris Instruments	Bottom sub	Borehole fluids	5 cm
	QL40-CAL	3 Arm Caliper	ALT/Mount Sopris Instruments	In-line sub	Borehole wall	5 cm
	QL40-FTC	Fluid Temperature and Conductivity	ALT/Mount Sopris Instruments	Bottom sub	Borehole fluids	5 cm
	QL40-OBI	Optical Borehole Imager	ALT/Mount Sopris Instruments	Bottom sub	Borehole wall	2 mm 360 points/revolution
	QL40-ABI	Acoustic Borehole Imager	ALT/Mount Sopris Instruments	Bottom sub	Borehole wall, inclinometry	2–4 mm 144–288 points/revolution
Stand-alone	DLL3	Dual Focused Resistivity	Geovista	NA	Formation	5–10 cm
	EM51	Magnetic Susceptibility and Induction	Geovista	NA	Formation	5–10 cm

Notes: ALT is advanced logic technology. QL stands for quick link.

By using processed camera data in combination with deviation sensor data, the tool can generate an unwrapped image oriented by 360°. Image quality degrades with hole diameters larger than 15 cm (6 in.) and with the presence of mud in the borehole, as the tool is designed for logs either in air or clear water. The OBI tool cannot be used in the presence of mud cake. During Expedition 364, OBI images during up logs were acquired with various resolutions, ranging from 360 samples by 4 mm or 360 samples by 2 mm (Table 1, Morgan et al., 2017).

The ABI downhole tool used during Expedition 364 produces a 1.2 MHz ultrasonic pulse sent toward the borehole wall (https://www.alt.lu/). Both the amplitude and two-way travel time of its first echo from the borehole wall (geological formation) are recorded. Two-way travel-time data can be processed to calculate a 360° borehole caliper. To obtain a 360° image, a focusing acoustic mirror pivots around a central axis. As for the OBI images, the ABI images are oriented with respect to the magnetic north thanks to deviation sensor data and are displayed as an unfolded representation of the 360° view. The image resolution is determined by the user and depends on the number of measurements made in one rotation and the rate at which the tool is raised up the borehole while measurements are made. During Expedition 364, ABI40 acoustic images from up logs were acquired with various resolutions, ranging from 288 samples by 2 mm to 144 samples by 4 mm (Table 1, Morgan et al., 2017). Acquisition of the 1st echo is automatically picked within an acoustic reflection time window whose limits can be set up either automatically or manually by the operator. The latter is useful when the formation echo is weak and can be mixed with echoes, multiples, or when borehole fluid contains particles that return a false first echo. As for the OBI, image quality will degrade with hole diameters larger than 15 cm and with the presence of mud in the borehole fluid due to the higher attenuation of the ultrasonic pulse.

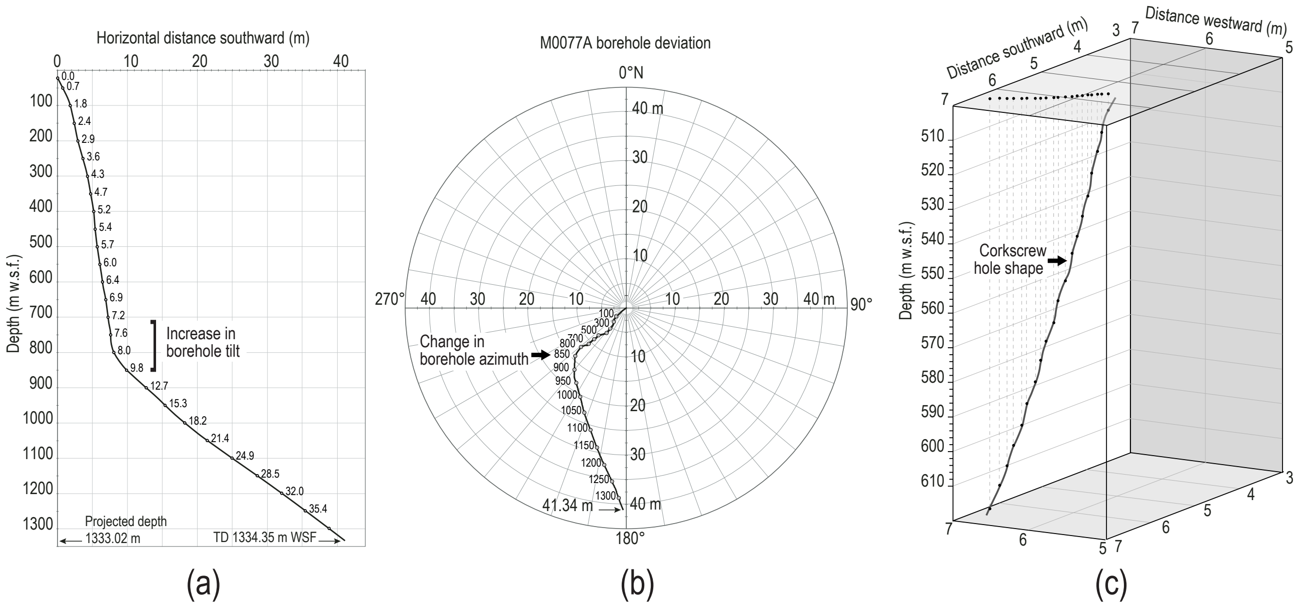

Figure 2. **(a)** true vertical depth and southward deviation of Hole M0077A. Note the increase in borehole tilt between 750 and 850 m w.s.f. **(b)** top view projection of the borehole path (modified from Gulick et al., 2017). Note the change in hole direction from southwest to southeast between 800 and 950 m w.s.f. **(c)** zoom on the 500–610 m w.s.f. interval in post-impact carbonates illustrating a corkscrew borehole shape. m w.s.f. is meter wireline depth below seafloor.

3 Logging-related features

Logging-related features arise from the downhole logging-data acquisition phase and mainly result from logging-tool eccentering, logging-tool malfunctions, and signal perturbation by an external factor (e.g., steel pipe for magnetic data).

3.1 Steel pipe and metal debris

Both the OBI and ABI contain a three-axis magnetometer and three accelerometers that allow for the orientation of the logging tools with respect to the magnetic north (azimuth) and vertical direction (tilt) to be determined. Such information can be used to compute the borehole's trajectory in 3-D (Fig. 2) and is key in orienting the borehole images with respect to the magnetic north. Consequently, any perturbation of the local earth's magnetic field to the borehole prevents the proper registration of the true magnetic north by the logging tool and results in incorrectly displayed or oriented borehole images. This problem is most commonly observed when, during up-log acquisition, the bottom entrance to the steel pipe or casing is approached as the presence of this ferrous metal locally distorts the magnetic field (e.g., Lofts and Bourke, 1999; Shipboard Scientific Party, 1993). During Expedition 364, this phenomenon has been clearly observed in both ABI and OBI data. In Fig. 3, perturbation in the ABI image and azimuth starts about 1.4 m below the casing entrance and increases upward (Fig. 3a, b, d). A deviation in the magnetic field intensity is also observed, starting ~ 2.5 m below the casing (Fig. 3e). The disturbance of the total magnetic field (Fig. 3e), calculated from the three magnetometer components (X, Y, Z), starts deeper than the one of the azimuth (Fig. 3d), which is derived from the radial components (X, Y). This is because the axial component of the pipe magnetization is stronger than the radial one. As a consequence, the axial component (Z) of the magnetometers on the logging tool is more influenced by the pipe further below than the radial components (X, Y) that are disturbed much closer to the pipe. Importantly, it is also notable that the depths at which the perturbations are observed below the pipe entrance are overestimated by ~ 1.2 m for both the ABI image and azimuth and the total magnetic field intensity logs. This is related to the way the ABI images are processed in the WellCAD software and how the depths of the various sensors are displayed. Indeed, for a given depth, the 360° ABI image is oriented with respect to the magnetic north thanks to the deviation sensor data that are acquired 1.2 m above the acoustic window data at the same instant. The magnetic field is thus assumed to be constant over this 1.2 m long interval, which is true most of the time, with the exception of the presence of a strong magnetic anomaly such as the one generated by the casing. As a consequence, the perturbation of the total magnetic field starts in reality about 1.3 m below the casing entrance while the perturbation of the azimuth occurs when the magnetometers inside the ABI almost reach the casing shoe. For future works on the IODP expedition 364 downhole magnetic data from Site M0077, both the azimuth and

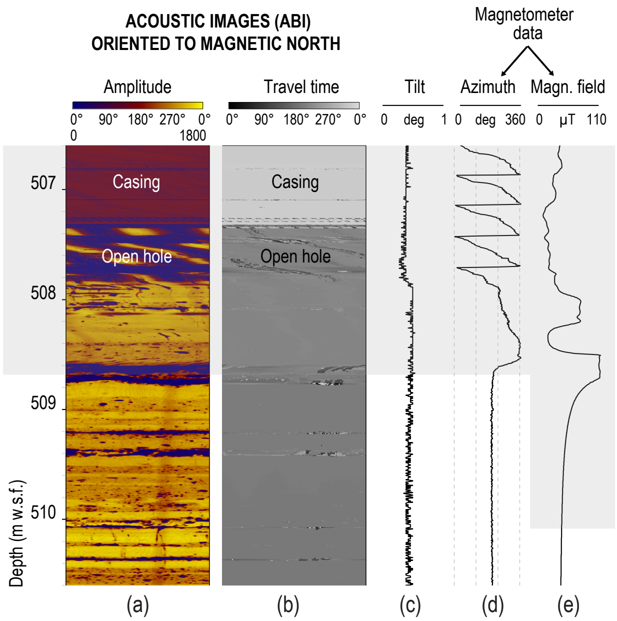

Figure 3. Commonly encountered magnetometer perturbation observed when approaching the entrance of a steel pipe or casing as the presence of metal close to the tool perturbs the magnetic field **(d, e)**. As a result, the acoustic borehole image is incorrectly displayed and oriented **(a, b)**. Grey shaded area indicates the zone under casing influence, overestimated here (see discussion in Sect. 3.1). m w.s.f. is meter wireline depth below seafloor.

magnetic field logs should thus be shifted upward by 1.2 m over the entire hole before any interpretation.

Localized perturbations in the magnetometer data have also been noted elsewhere in open hole along the borehole and may possibly be related to the presence of highly magnetized formations (Gaillot et al., 2004). The presence of pieces of metal lodged in the borehole wall as a consequence of technical difficulties during the drilling operations can also cause perturbations in the magnetometer data (e.g., azimuth and magnetic field spikes at ∼ 851 m w.s.f. in Fig. 4m). These metal pieces are also revealed by anomalous spikes on both the magnetic susceptibility (MSUS) and formation conductivity (IL) logs (e.g., ∼ 850 m w.s.f. on Fig. 4n). Note that the azimuth and magnetic field spikes are lying ∼ 1 m below the MSUS and IL spikes as a result of the 1.2 m processing offset previously discussed. Once corrected from this offset, all anomalies align coherently at the same depth (∼ 850 m w.s.f.).

3.2 Logging tool eccentering effect on images

Logging tool eccentering commonly occurs in non-circular holes or over intervals that are caved or washed out beyond the dimensions of the centralizers (e.g., Lofts and Bourke, 1999). As a consequence, the logging tool is no longer centered in the borehole. Not all the wireline logging tools are sensitive to eccentering, which particularly affects acoustic borehole imaging quality.

During Expedition 364, the ABI and OBI logging tools were run with two centralizers to ensure tool centralization. Yet, tool eccentering appears to have affected the ABI data across some depth intervals. Tool eccentering is generally expressed by dark and light stripes on the amplitude images, as eccentering causes the amplitude to increase at azimuths where the tool is closer to the borehole wall, and vice versa (e.g., Lofts and Bourke, 1999). In Hole M0077A, logging-tool eccentering is illustrated in Fig. 5 by two sets of ABI data acquired over the same depth interval (Fig. 5-1 and 5-2). Travel-time cross sections clearly illustrate the non-circular shape of the hole over this interval (Fig. 5c, f). On the amplitude images two dark stripes (see blue arrows in Fig. 5a, d) appear as regular, almost vertical non-planar features that are not randomly oriented. Their azimuths are highlighted by the bold blue lines on the travel-time cross sections (Fig. 5c, f). They correlate with portions of the borehole wall that are orientated obliquely with respect to the incident angle of the acoustic wave. This sloping angle of incidence is likely to lead to signal scattering over these sections of the borehole and be associated with low amplitudes in the recorded data. The amplitude of the acoustic signal indeed depends on the surface roughness of the borehole wall, the acoustic impedance contrast between the borehole fluid (or mud cake) and the formation, the attenuation in the borehole fluid, and the angle of incidence. In this case, logging-tool eccentering is not expressed by the classical dark and light stripes at 180° from each other (Lofts and Bourke, 1999), probably because the eccentering occurs in a non-circular-shaped hole (Fig. 5c and f) instead of a circular one.

Over the same interval, the azimuths of the two dark stripes are not the same when comparing Up-log 1 (Fig. 5a, c) and Up-log 2 (Fig. 5d, f). This difference suggests that the position of the logging tool in the hole was different, and that the tool followed two different trajectories during the successive up-logs. The amplitude images acquired on up-logs 1 and 2 (Fig. 5a, d) have been merged (Fig. 5g). The resulting image clearly shows an abrupt jump in the orientation of the dark low amplitude stripes at ∼ 610.6 m w.s.f. This feature, which is entirely related to eccentering, should not be misinterpreted and taken as an incorrect display or orientation of one of the two ABI images (either Up-log 1 or Up-log 2). Indeed, the correct orientation of both Up-log 1 and Up-log 2 images is confirmed by the "F" sedimentary feature which displays the same orientation on each of the amplitude and travel-time images (white arrows in Fig. 5a, b, d, e, g).

4 Drilling-related features

Drilling-related features are physically produced during the drilling or coring phase. They include any operation that may have affected the shape or trajectory of the hole (e.g., ream-

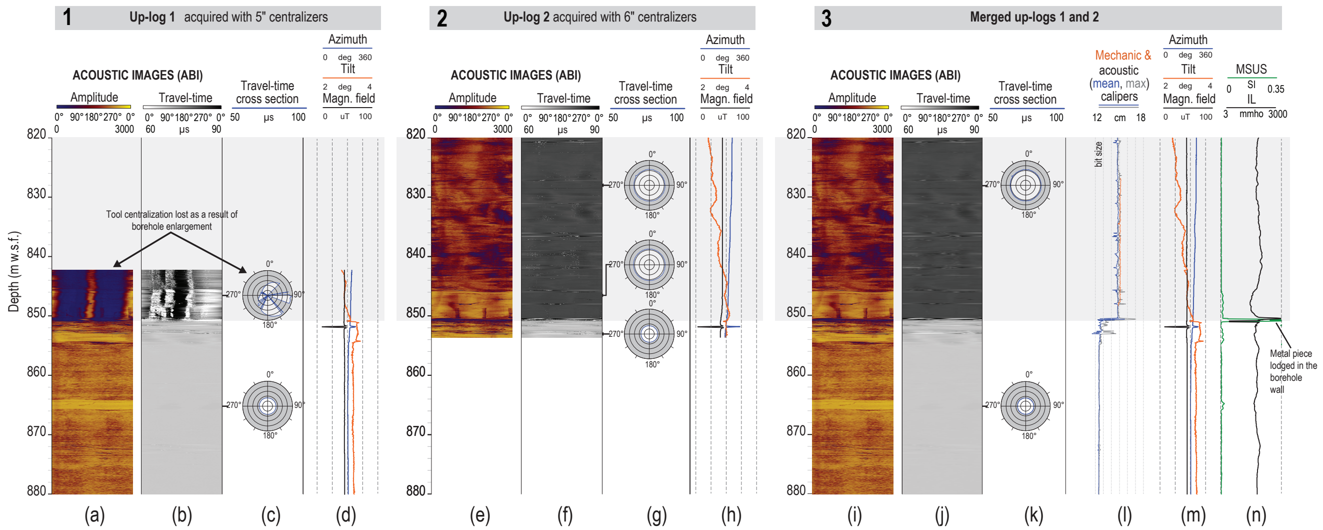

Figure 4. Drilling induced borehole enlargement as a result of fallen metal pieces (see discussion in Sect. 4.3). (1) Up-log 1; (2) Up-log 2; (3) merged Up 1 and Up 2 logs. Change in borehole diameter is evidenced at ∼ 850 m w.s.f. by acoustic borehole image data **(b, f, j, l)**. The presence of steel pieces lodged in the borehole wall at the same depth is highlighted by azimuth, magnetic field, magnetic susceptibility, and conductivity spikes **(m, n)**. Note that the travel-time cross sections' lower limits have been set to 50 µs **(c, g, k)**. m w.s.f. is meter wireline depth below seafloor.

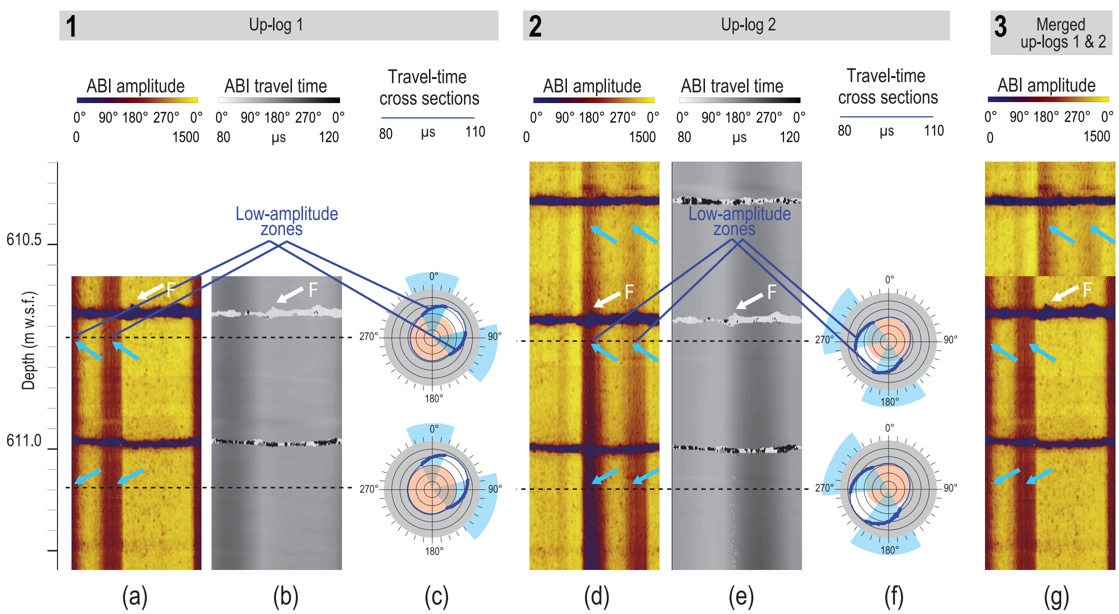

Figure 5. Example of tool eccentering effect in a non-circular borehole. (1) Up-log 1; (2) Up-log 2; (3) merged Up 1 and Up 2 logs. Two dark low-amplitude stripes (blue arrows) are observed on the ABI amplitude images **(a, d)**. Their location is highlighted with the bold blue lines on the travel-time cross sections **(c, f)**. Over the same interval, the azimuth of these stripes varies depending on the up-log (1 or 2), resulting in a stepped change in stripe orientation on the merged image **(g)**. This is interpreted as a change in tool eccentering between the two successive acquisition passes. The sedimentary feature "F" (white arrows), which shows the same azimuth on both up-logs **(a, d, g)**, attests to the correct orientation of both sets of images. Note that travel-time cross sections' lower limits have been set to 80 µs **(c, f)**. m w.s.f. is meter wireline depth below seafloor.

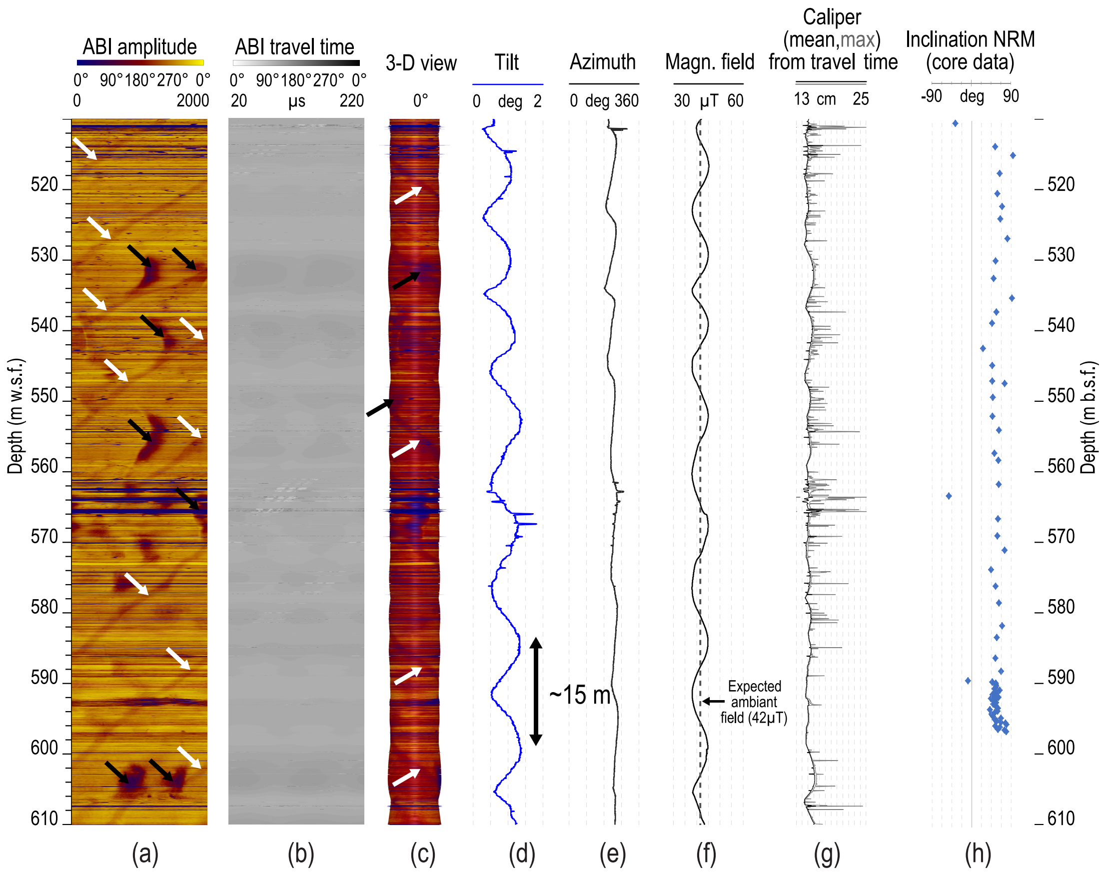

Figure 6. Drilling-induced corkscrew borehole shape in the post-impact carbonates, possibly due to drill bit wobble, steel wedged at the bit or overfeed of rods. This shape (see also Fig. 2c) is evidenced by cyclic oscillations in both accelerometer (tilt) and magnetometer (azimuth) data **(d, e)**. One continuous regular spiraling narrow dark stripe (white arrows in **a** and **c**) may result of the drill pipe rubbing on the carbonate formation. Drilling induced re-magnetization of the formation is tentatively proposed to account for the cyclic changes observed in the magnetic field **(f)**. **(h)** Non-demagnetized NRM measured on core samples dominated by positive inclination (indicative of normal polarity), suggesting a pervasive normal polarity remagnetization. m w.s.f. is meter wireline depth below seafloor; m b.s.f. is meters below seafloor.

ing), drill marks on the borehole wall, and the in situ pollution by debris produced by the drilling operations (e.g., here, metal pieces of casing and stuck drill bits that were ground up).

4.1 Corkscrew hole and formation re-magnetization

Boreholes are rarely drilled as perfect vertical cylinders. In particular, some drilling operations can cause the borehole to take the shape of a corkscrew (spiral). Such a shape can result from drilling and reaming operations including the bit-whirl and wiper trips. In the post-impact carbonates at Site M0077, 10 to 15 m long regular undulations are observed in both the tilt and azimuth of the ABI logging-tool data between 510 and 610 m w.s.f. (Fig. 6d, e). Tilt and azimuth are provided by two distinct types of sensors, accelerometers (accuracy: ±0.5 degree) and magnetometers (accuracy: ±1.2 degree), respectively. The observed undulations are interpreted as reflecting a corkscrew shaped hole (see zoom of the borehole trajectory over this depth interval in Fig. 2c). Oscillations <2 cm in the acoustic borehole caliper are also observed with a shorter wavelength (2–8 m). The local presence of one or two large low-amplitude dark stripes on the ABI amplitude image (black arrows in Fig. 6a, c) occurred where the borehole shows a non-circular shape and is enlarged. As discussed in Sect. 3.2, these stripes possibly reflect logging-tool eccentering. Superimposed on these possible eccentering features, the amplitude image also displays one continuous, spiraling, narrow dark stripe (white arrows in Fig. 6a, c) wherein the path is independent of the changes in borehole diameter and shape in cross section. A clear link is, however, observed between the orientation of this stripe and the tilt and azimuth (Fig. 6a, d, e). The origin of the stripe remains unclear, but based on the tight link with borehole geometry, we suggest that it may reflect a mark on the borehole wall (see also Sect. 4.2) resulting from the drill pipe rubbing the carbonate formation during operations. This can occur as the bit engages the formation and the stand drill-pipe torques into a helical.

At the drill site, the expected ambient field intensity as given by the World Data Center for Geomagnetism (http://wdc.kugi.kyoto-u.ac.jp/index.html, last access: 12 October 2018) is ∼ 42 µT (Fig. 6f), which corresponds to the mean intensity value measured by the magnetometers over the 510 and 610 m w.s.f. intervals. However, apparent 10–15 m long cyclic oscillations in the local magnetic field are also observed with values ranging between 38.2 and 45.5 µT (Fig. 6f). These oscillations in the magnetic field intensity (as measured by the magnetometers) vary jointly with the borehole tilt (as measured by the accelerometers). High values in the local magnetic field (Fig. 6f) correlate with high tilts (Fig.6d), and vice versa. We tentatively interpreted this cyclical pattern in magnetic field intensity as a possible drilling-induced magnetization overprint in the surrounding rocks. Indeed, in the 510 and 610 m w.s.f. interval, the lithology mainly consists of marlstone and limestone (Morgan et al., 2017) with low coercivity (Urrutia-Fucugauchi et al., 2017). Such material is susceptible to acquiring drilling-induced magnetization (e.g., Jackson and Van der Voo, 1985). The effect of drilling and sawing on the magnetization of rocks is a known phenomenon, and the magnetic overprint imparted by the drill string is a problem commonly encountered in cores taken by the IODP (e.g., Fuller et al., 1998). Preliminary paleomagnetic measurements performed on discrete samples within this depth interval (Fig. 6h) suggest that a pervasive normal polarity re-magnetization of the carbonates likely occurred within the low-coercivity fraction of magnetic grains, supporting the idea that overprinting may readily occur in this formation. Therefore, we suggest that the drilled carbonates have undergone magnetization overprinting during the drilling operations possibly as a result of the rotary perforation of the formation associated with the presence of a steel BHA, steel wedged at the bit or overfeed of rods. As the changes in ambient field intensity follow the changes in the borehole tilt, we also suggest a possible link between the degree of drilling-induced magnetization and the drilling conditions that cause the borehole to take the shape of a corkscrew.

4.2 Borehole wall drilling marks

During Expedition 364, helical stripes with a wavelength of ∼ 0.2 m are observed locally on the borehole wall images acquired in the peak-ring granitoids (Fig. 7). They are evidenced through either low amplitudes zones on the ABI images or dark zones the OBI images (arrows in Fig. 7a, b, d). They are also slightly visible on the travel-time images (Fig. 7a). Unlike the corkscrew related stripes (see Sect. 4.1 above), these stripes are not associated with any changes in the borehole tilt or azimuth (Fig. 7e, f). They are interpreted as drilling-induced markings on the borehole wall, left by a drilling tool in a relatively soft, shock-metamorphosed granite with an unusually low density (Morgan et al., 2016, 2017; Christeson et al., 2018).

In another example, at a larger scale, a low amplitude, dark stripe (Fig. 8d) is observed in the lower half of the hole (Fig. 8d) where the tilt is increased to about 4.2° (Fig. 2a and b). The mean orientation of the path of the stripe is ∼ 25° N (Fig. 8d). Orienting the image to the high side (Fig. 8g) instead of to the magnetic north (Fig. 8d) clearly shows that the stripe is parallel to the axis of the hole, thus illustrating a clear link between the presence of this stripe and the borehole inclination. We thus tentatively interpreted this large-scale stripe as a key-seat-related feature that developed in the inclined part of the hole because the drill pipe was rubbing the bottom side of the borehole. However, no clear groove cut is observed on the acoustic caliper data (Fig. 8f). In addition, the stripe is not oriented to 180° (i.e., aligned on the lowest part of the hole), as expected from a key seat, but at ∼ 220°, i.e., with an offset of ∼ 40° (Fig. 8g) westward. This angular offset may result from the change in azimuth of the hole observed at 850 m w.s.f. (Fig. 2b), which deviated the drill pipe and forced it to the lateral westward side of the borehole.

4.3 Drilling induced borehole enlargement

Below ∼ 700 m w.s.f., the borehole shape at Site M0077 was good to excellent (Fig. 1e). During up-log ABI data acquisition, logging-tool centralization was however lost at ∼ 850 m w.s.f. (Fig. 1d), suggesting drastic borehole enlargement. The tool string was brought back to the surface and the 5″ centralizers replaced by 6″ centralizers. These later allowed for a proper centralization of the logging tool string from 850 to ∼ 702 m w.s.f. (casing entrance). As shown in Fig. 4l, this borehole enlargement is confirmed by acoustic travel-time data that evidence a change in diameter from ∼ 12.5 cm (close to the outside diameter of the drill bit of 12.26 cm) below 850 m w.s.f. to ∼ 14.7 cm (∼ 2.5 cm larger than the outer bit diameter) above 850 m w.s.f. (Fig. 1a). The enlarged borehole diameter is observed over the entire 850–702 m w.s.f. interval (Fig. 1e).

No clear explanation exists to account for this oversized borehole since (1) although the drill bit has been replaced by a new one at 823.24, 829.34 and 851.65 DSF (driller's depth below seafloor), the entire 702–1334 m b.s.f. interval was nominally drilled with the same bit size (Fig. 1a), and (2) no major change in lithology is observed at 850 m w.s.f., except for the presence of a ∼ 5 m thick dolerite dike intrusion, extending from 846.3 to 851.1 m b.s.f. (Fig. 1c). This dike is characterized by a high amplitude on the ABI image (yellowish color in Fig. 4e, i), as dolerites are harder than the surrounding granite. It also has a higher magnetic susceptibility (Fig. 4n), as dolerites are enriched in iron compared to granitoids. The change in lithological properties when entering in the dolerite dike was probably responsible for the need to change the drill bit at ∼ 851 DSF. However, it cannot

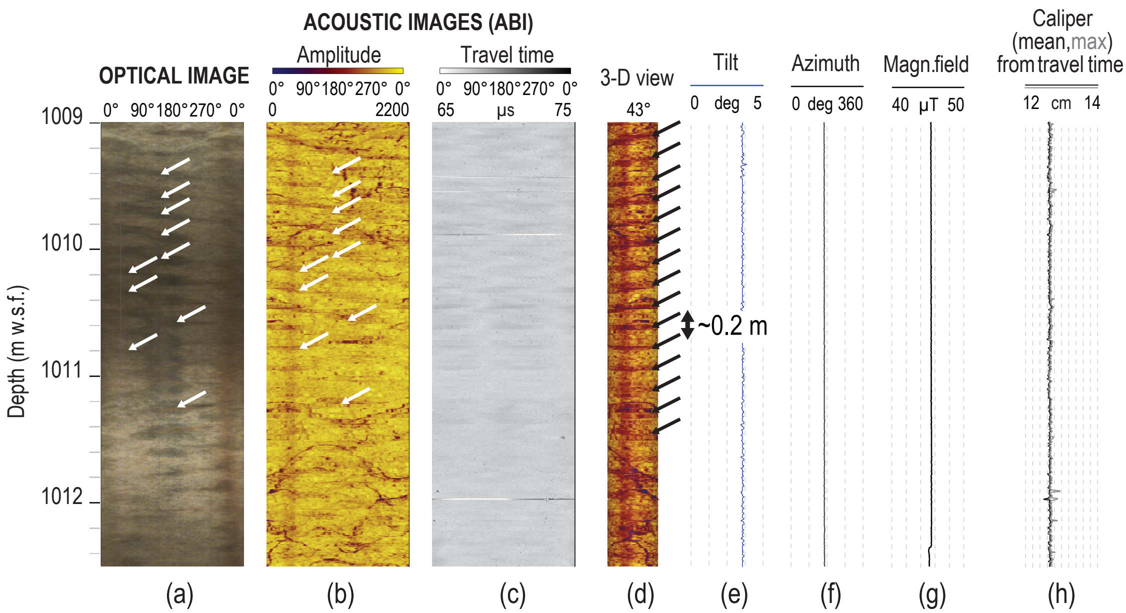

Figure 7. Drilling-induced helical marking on the borehole wall, evidenced by helical stripes (arrows) on both the optical and acoustic borehole images. m w.s.f. is meter wireline depth below seafloor.

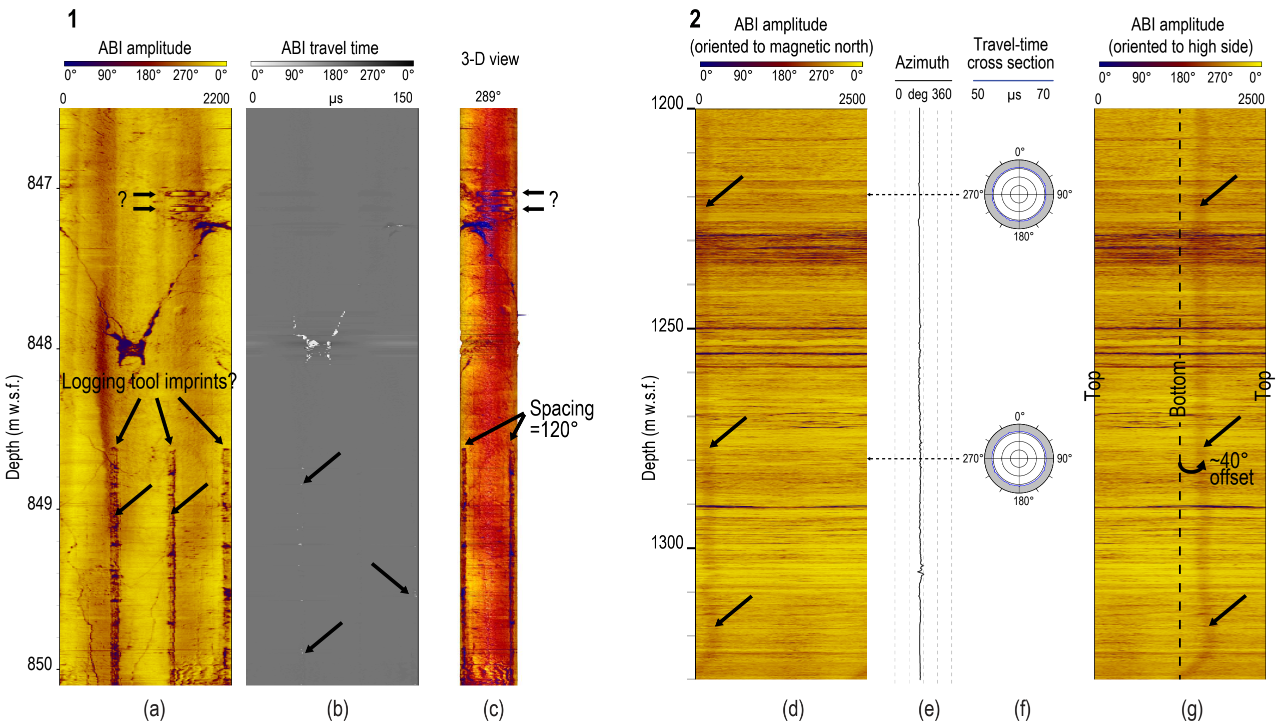

Figure 8. Marks on the borehole wall. (1) possible tool imprint oriented to 120°, and residue possibly left in mud residue by arms of the mechanical caliper. (2) ABI image oriented with respect to the magnetic north **(d)** and to the high side, **(g)** illustrating that the continuous regular narrow dark stripe (black arrows) is closely related to borehole inclination and may be the result of the drill pipe rubbing on the borehole wall. **(f)** travel-time cross section (magnetic north orientation) illustrates a regular borehole shape with no evidence for groove cut to be associated with the narrow dark stripe. Note that the travel-time cross sections' lower limit has been set to 50 μs.

explain why the borehole diameter is oversized above that depth.

Besides the change in borehole diameter, large spikes in both conductivity and magnetic susceptibility are also noticeable at ∼ 850 m w.s.f. (Fig. 4n). These anomalies are not observed on resistivity and magnetic susceptibility MSCL data acquired on whole round cores taken at the same depth (Morgan et al., 2017), and we consequently interpret these spikes as reflecting the presence of pieces of metal lodged in the borehole wall. This interpretation appears to be confirmed by pieces of steel that were found in the liners of cores 136R–138R (850.6–852.9 m DSF), among which a large piece (> 1 cm) of a casing shoe found in the liner of core 137R (Fig. 1a) and coming from the casing shoe positioned at ∼ 702 m w.s.f. Some other pieces possibly come from a misaligned casing located at ∼ 307 m w.s.f., which we drilled through during the coring operations, as well as from a broken drill bit (Fig. 1a, picture of drill bit replaced at 701.6 m DSF). In order to explain for the oversized borehole diameter over the 702–850 m w.s.f. interval, we tentatively suggest that some large pieces of casing shoe and damaged drill bit were trapped outside the drill bit during the coring phase, which led to an enlargement of the hole over this entire interval in the relatively soft granitic basement. The damages done to the successive drill bits are illustrated in Fig. 1a (pictures of drill bits replaced at 823.2 and 829.3 m DSF). Although the hole shape remained relatively subcircular, a change in borehole quality is clearly observed on both the ABI amplitude image (Fig. 4i) and mean caliper (Fig. 4l) when crossing 850 m w.s.f., with a smoother borehole below 850 m w.s.f. and a more rugose one just above. The presence of these pieces of metal outside the drill bit also seems to have affected the borehole trajectory at some point, since a drastic increase of the borehole tilt and a clear change in the borehole azimuth are observed from ∼ 750 to 850 m w.s.f. (Fig. 1f and Fig. 2a, b). The above observations are a nice example of how operational difficulties at shallower depths indirectly induced changes in borehole diameter, shape and trajectory at greater depths.

Just before the change in borehole diameter described above, we noticed the presence in both the amplitude and travel time of borehole images of an unusual feature consisting of three vertical narrow stripes oriented to 120° and extending from 846 to 850.4 m w.s.f. (Fig. 8a, b). This feature cannot be interpreted as drill marks (see also Sect. 4.2) on the borehole wall, since no drill tool with such a shape has been used during the drilling/coring operations. We believe that these marks have been left by the three arms of the mechanical caliper in a thin layer of mud residue covering the borehole wall. This mud may have been left over from the formation during flushing because of the borehole enlargement and associated increase in the annular space between the pipe and the geological formation, thus reducing annular circulating fluid velocity. If this interpretation is correct, this is an example of a combined drilling- and logging-induced feature. Above these vertical imprints, two sub-horizontal features are observed at ∼ 847 m w.s.f. (Fig. 8a). Their origin remains unknown so far.

5 Conclusions

Differentiating geological features from operation-related features is critical for downhole logging-data quality control and interpretations. High quality data were acquired downhole with slimline tools during the IODP–ICDP Expedition 364. Yet, some non-geological features are observed and illustrated in this paper. Such features are grouped in two families: logging-related and drilling-induced features. We mainly focus on acoustic borehole images that provide invaluable source of information for sub-surface geology characterization but are also very sensitive to acquisition context and borehole conditions. Slimline tools are often used in MSP expeditions (e.g., IODP Expeditions 310, 313, 325, 364, 381), as MSPs employ various coring technologies and pipe sizes that provide constraints on the diameters of logging tools to be used. This methodology is different from other IODP platforms, the JOIDES Resolution and the Chikyu, where the fixed larger pipe sizes allow larger diameter standard sets of logging tools to be deployed. The logging-related and drilling-induced features presented and discussed in this paper are based on data acquired with slimline tools, but most of them should be valid for standard tools.

Data availability. Downhole logging data are stored and made available on the IODP log database (see also page 3, second paragraph in this article): http://mlp.ldeo.columbia.edu/logdb/scientific_ocean_drilling/

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Science Reports

Colorado Plateau Coring Project, Phase I (CPCP-I): a continuously cored, globally exportable chronology of Triassic continental environmental change from western North America

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Abstract. Phase 1 of the Colorado Plateau Coring Project (CPCP-I) recovered a total of over 850 m of stratigraphically overlapping core from three coreholes at two sites in the Early to Middle and Late Triassic age largely fluvial Moenkopi and Chinle formations in Petrified Forest National Park (PFNP), northeastern Arizona, USA. Coring took place during November and December of 2013 and the project is now in its post-drilling science phase. The CPCP cores have abundant detrital zircon-producing layers (with survey LA-ICP-MS dates selectively resampled for CA-ID-TIMS U-Pb ages ranging in age from at least 210 to 241 Ma), which together with their magnetic polarity stratigraphy demonstrate that a globally exportable timescale can be produced from these continental sequences and in the process show that a prominent gap in the calibrated Phanerozoic record can be filled. The portion of core CPCP-PFNP13-1A for which the polarity stratigraphy has been completed thus far spans ∼ 215 to 209 Ma of the Late Triassic age, and strongly validates the longer Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) based on cores recovered in the 1990s during the Newark Basin Coring Project (NBCP).

Core recovery was ∼ 100 % in all holes (Table 1). The coreholes were inclined ∼ 60–75° approximately to the south to ensure azimuthal orientation in the nearly flat-lying bedding, critical to the interpretation of paleomagentic polarity stratigraphy. The two longest of the cores (CPCP-PFNP13-1A and 2B) were CT-scanned in their entirety at the University of Texas High Resolution X-ray CT Facility in Austin, TX, and subsequently along with 2A, all cores were split and processed at the CSDCO/LacCore Facility, in Minneapolis, MN, where they were scanned for physical property logs and imaging. While remaining the property of the Federal Government, the archive half of each core is curated at the NSF-sponsored LacCore Core Repository and the working half is stored at the Rutgers University Core Repository in Piscataway, NJ, where the initial sampling party was held in 2015 with several additional sampling events following. Additional planned study will recover the rest of the polarity stratigraphy of the cores as additional zircon ages, sedimentary structure and paleosol facies analysis, stable isotope geochemistry, and calibrated XRF core scanning are accomplished. Together with strategic outcrop studies in Petrified Forest National Park and environs, these cores will allow the vast amount of surface paleontological and paleoenvironmental information recorded in the continental Triassic of western North America to be confidently placed in a secure context along with important events such as the giant Manicouagan impact at ∼ 215.5 Ma (Ramezani et al., 2005) and long wavelength astronomical cycles pacing global environmental change and trends in atmospheric gas composition during the dawn of the dinosaurs.

1 Context and motivation

Bracketed between two of the largest mass extinctions, the Triassic Period (ca. 252–202 Ma) saw the evolution of the major elements of modern animal communities on land, had arguably the highest atmospheric CO_2 concentrations of the Phanerozoic (Foster et al., 2017) (>4000 ppm: Schaller et al., 2015), and has the longest recovered continuous records of orbitally paced climate change (Olsen and Kent, 1996; Ikeda and Tada, 2014; Kent et al., 2017) – one that bears the fingerprint of the chaotic evolution of the Solar System (Olsen and Kent, 1999; Ikeda and Tada, 2013) (Fig. 1). By the Late Triassic, continental tetrapod associations were remarkably segregated into latitudinal zones, and although dinosaurs had evolved by the beginning of that epoch, herbivorous forms were restricted to high latitudes, while in tropical communities carnivorous dinosaurs remained a relatively minor part of communities, tending also to be rather small (Whiteside et al., 2015). In the oceans, during this time, calcareous nanoplankton made their appearance (Bown et al., 2004), modern reef-forming corals evolved (Stanley, 1981), and archaic forms such as conodonts declined (Tanner et al., 2004).

But despite the pivotal role of the Triassic, the period is characterized by very poor chronologic constraints. This has been especially true for the longest age (stage) of the Triassic, the Norian (∼ 206–228 Ma), arguably the acme of Triassic life and the longest age of the Phanerozoic. As of 2011, there were only three U-Pb zircon dates over the 22 Myr time interval available to constrain the stage (see Olsen et al., 2011), and even its boundary ages and especially marine to continental correlations have remained hotly contested (Muttoni et al., 2004; Ogg et al., 2012). The Late Triassic–Early Jurassic astrochronology and associated paleomagnetic polarity stratigraphy from the largely lacustrine Newark Basin based on cores mostly from the NSF-funded Newark Basin Coring Project (NBCP) completed in the mid-1990s served as the basis of a high-resolution timescale and has been broadly accepted (e.g., Walker et al., 2013; IUGS/ISC, 2017). However, because it was pinned by radioisotopic dates only at the top of the Triassic age section, its accuracy has been questioned from a number of fronts (e.g., Hilgen et al., 1997; Tanner and Lucas, 2015), including largely biostratigraphically based assertions of the presence of cryptic but significant gaps in the upper part of the Triassic age section that would separate the dated levels from 1000s of meters of the underlying section (Gallet et al., 2003; Kozur and Weems, 2005; Tanner et al., 2004).

Progress in past Earth system science fundamentally depended on being able to measure time at appropriate levels of resolution and also being able to link contemporaneous events, fossil occurrences, and environmental records across geography, and this ability has been sorely lacking for many time intervals in Earth's history. To address

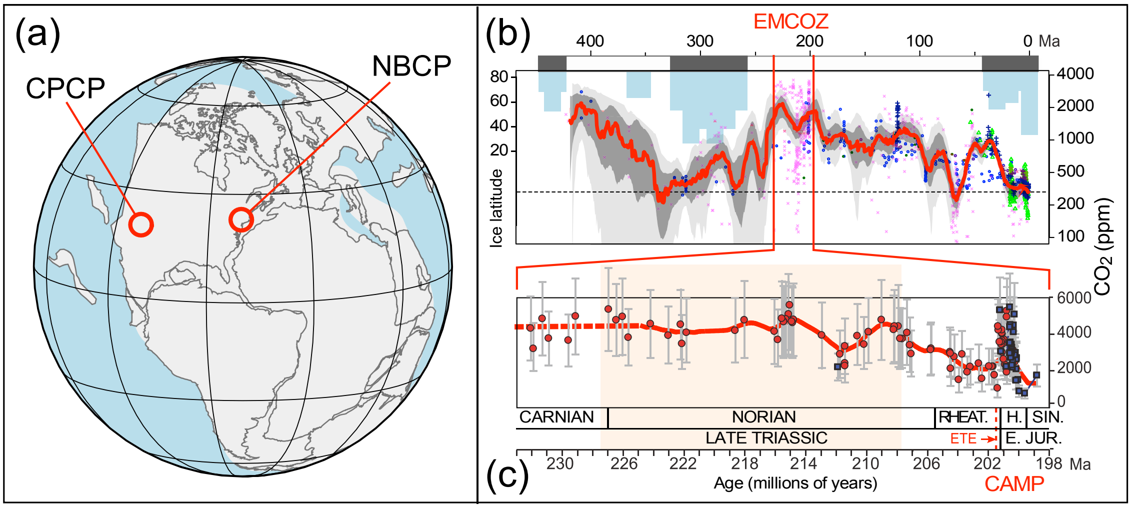

Figure 1. Context for the CPCP cores. **(a)** Late Triassic–Early Jurassic Pangea showing the positions of CPCP cores and Newark Basin Coring Project (NBCP) APTS (based on Whiteside et al., 2010). **(b)** Compilation of CO_2 proxy data and extent of continental ice modified from Foster et al. (2017) with latitudinal extent of ice (light blue bars) and ice-house conditions (grey bars). Proxy symbols are leaf stomata, blue open circles; pedogenic carbonate, pink crosses; boron isotopes, green triangles; liverworts, blue filled circles; and alkenones, blue crosses – red line is fit through the data and 68 % and 95 % confidence intervals are dark and light grey bands. **(c)** The Early Mesozoic CO_2 Zenith (EMCOZ), based on the pedogenic CO_2 proxy from the Newark and Hartford basins, modified from Schaller et al. (2015): red circles are from the Newark Basin and blue circles are from the Hartford Basin; light orange area is interval encompassed by the Chinle Formation in CPCP cores; red line is the smoothed fit through the data; and the dashed red line mean for the points without astrochronologic time control.

this cross-cutting issue for the Triassic, we launched the Colorado Plateau Coring Project (CPCP) as an interdisciplinary multiphase coring experiment in a geologic setting where there was sufficient background information to know there would be abundant zircon U-Pb datable deposits and a recoverable paleomagnetic polarity record that together would allow for a meaningful, globally exportable timescale. Also, deemed highly desirable, would be the selection of a target where cores would leverage, and allow for correlation with, a large amount of previously collected surface information. The CPCP was an outcome of the 1999 US NSF- and ICDP-funded "International Workshop for a Climatic, Biotic, and Tectonic, Pole-to-Pole Coring Transect of Triassic-Jurassic Pangea" (http://www.ldeo.columbia.edu/~polsen/nbcp/westpangea.html, last access: September 2018) that recognized "Western Equatorial Pangea (Colorado Plateau)" as a key coring target. Subsequent CPCP workshops held in 2007 and 2009 (funded by the US NSF, ICDP, and DOSECC) narrowed down the optimal site for the first phase of the CPCP to Petrified Forest National Park, in northern Arizona (Fig. 2) (Olsen et al., 2008; Geissman et al., 2010; http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html, last access: September 2018), where strata of the ?Early–Middle Triassic age Moenkopi Formation and Late Triassic Chinle Formation are well represented and have been comparatively very well studied in previous projects, some of which demonstrated that zircon U-Pb geochronologic information (Riggs et al., 2003) and paleomagnetic polarity stratigraphies (Steiner and Lucas, 2000; Zeigler et al., 2017) could be recovered. Furthermore, long-term study (Parker and Martz, 2011) of the superb exposures of Petrified Forest National Park (PFNP) had resulted by that time in a well-characterized physical stratigraphy (Woody, 2006; Martz and Parker, 2010; Martz et al., 2012), into which rich assemblages of vertebrates (Long and Murry, 1995; Parker and Irmis, 2005) and plants (Ash, 1972, 1989; Fisher and Dunay, 1984; Litwin, 1991), and their environments (Therrien and Fastovsky, 2000) were registered (Parker, 2006). These outcrops also have the best record of what is arguably the most prominent continental biotic transition of the Late Triassic (prior to the end Triassic extinction), the Adamanian–Revueltian Biozone boundary (Parker and Martz, 2011; Martz and Parker, 2017) that seems plausibly linked to the great Manicouagan bolide impact (Ramezani et al., 2005; Parker and Martz, 2011; Olsen et al., 2011). Proposals were submitted in 2010 and funding was secured from both the US NSF and ICDP by 2013 to recover a continuous cored record of the Triassic record in PFNP. The CPCP, Phase I scientific coring experiment designed to explicitly test competing Triassic stratigraphic, temporal, climatic and biotic hypotheses took place during November and December of that same year, and involved drilling at northern and southern locations in Petrified Forest National Park (Figs. 2, 4).

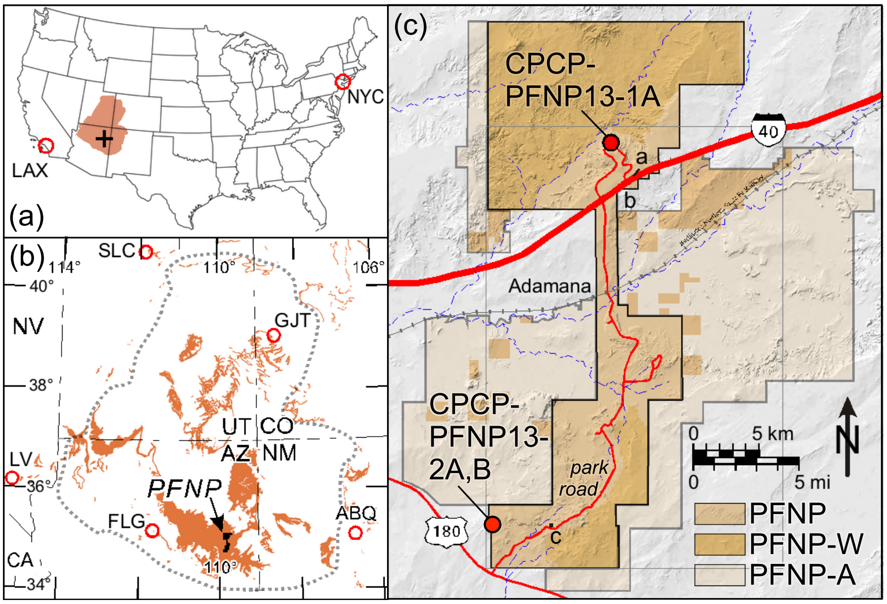

Figure 2. Location of CPCP cores. **(a)** Location of the Colorado Plateau (red-brown area) in the United States with the cross marking the location of the coring sites in Petrified Forest National Park: LAX, Los Angeles, California; NYC, New York City, New York, which is just to the east and south of the location of the Newark-Hartford APTS (NBCP cores and outcrops). **(b)** outline of the Colorado Plateau (dotted line) and Triassic outcrop area (red brown) showing the location of Petrified Forest National Park (PFNP): ABQ, Albuquerque, New Mexico (NM); FLG, Flagstaff, Arizona (AZ); GJT, Grand Junction, Colorado (CO); LV, Las Vegas, Nevada (NV); SLC, Salt Lake City, Utah (UT); CA, California. **(c)** Map of PFNP with location of the coring sites: PFNP, Petrified Forest National Park; PFNP-A, Private or State Trust land; PFNP-W, Petrified Forest National Park, Wilderness area; a, park headquarters; b, park entrance off I-40; c, Rainbow Forest Museum; PFNP-CPCP13-1A, core site at Chinde Point; PFNP-CPCP13-2A, 2B, core site at "West Bone Yard".

1.1 The need to core

Despite the superb outcrops of Triassic strata in parts of the American Southwest, a scientific drilling experiment was essential because most continuous sections in outcrop are either inaccessible in vertical cliffs or are weathered and geochemically altered, making observations and sampling at the appropriate level of detail impossible. Furthermore, the characteristic shallow bedding attitudes in combination with lateral facies changes typical of these largely fluvial systems compromise the ability to determine superposition in sections compiled over long geographic distances. This is especially clear at PFNP, where there are two main outcrop areas, a northern area with the stratigraphically higher parts of the sections and a southern area with the stratigraphically lower Chinle sections. These outcrop areas are separated by about 20 km of no exposure; although the sections have been individually quite well studied, no two analyses of the combined stratigraphic column published in 20 years agreed, some compilations differing by as much as 30 % in total thickness. Additionally, the lowermost parts of the Chinle Formation and underlying Triassic Moenkopi Formation do not crop out in the park. The situation is worse in other areas of the American Southwest.

1.2 Tectonic environment

The overall tectonic context of early Mesozoic strata in the American Southwest is uncertain, because, compared to the relatively simple Triassic–Jurassic extension and continental rifting of central Pangea, including eastern Laurentia, models of the western North American Cordillera are complex, involving exotic terranes, magmatic arcs, oceanic-plate subduction, and intense crustal deformation lasting until the early Cenozoic, with most of the pertinent tectonic geometry being so strongly deformed as to be inferable only by indirect means. Since the 1970s the leading hypothesis for the tectonic context of the mostly continental Triassic–Jurassic sequences was that they developed during eastwardly directed oceanic-crust subduction of the Farallon Plate beneath North America with a magmatic (Cordilleran) arc over the subducting slab and west of the backarc, back-bulge, backarc tectonic furrow, or foreland retroarc basins in which the Triassic–Jurassic deposits accumulated (Burchfiel and Davis, 1972; Lawton, 1994; Gehrels et al., 2000; Barth and Wooden, 2006; Sigloch and Mihalynuk, 2017; Dickinson, 2018) (Fig. 3). An alternative and controversial model based on geologic and geophysical (tomographic) data postulates that western North America was a passive continental margin from the Paleozoic until the Cretaceous with westward-

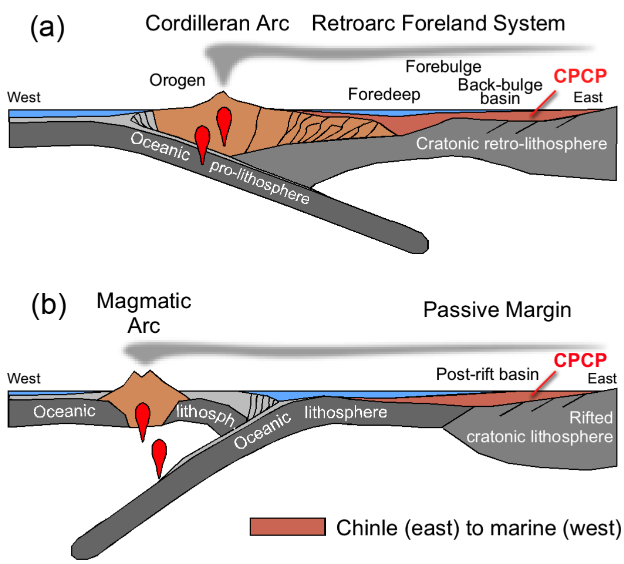

Figure 3. Generalized cartoons of end-members of the alternative tectonic models for the Chinle basin (at position of CPCP in red). **(a)** Conventional model of a Triassic Cordilleran arc with a retroarc basin with Chinle and marine strata (modified and generalized from Eriksson et al., 2008; DeCelles and Giles, 1996). **(b)** Passive margin model for Triassic western North America (modified from Chemenda et al., 1997) which is consistent with Hildebrand (2013). Note that realistic, empirically based cross sections for these end-member models have yet to be published and that these are cartoons based on possible analog situations, with the additional caveat that the significant possibility of large strike–slip components (non-plane strain) is not addressed in this figure. Note also that Chinle was probably in a belt of easterly (trade) winds at the time.

dipping subduction (Hildebrand, 2009; Sigloch and Mihalynuk, 2013). Despite the extreme differences, both models are consistent with having most of the sediment of the Triassic–Jurassic sequences derived from northwesterly flowing fluvial systems, with a persistent slope from the interior of Pangea as well as closer topographic remnants of the Ancestral Rocky Mountain orogen, toward the Cordilleran margin (Riggs et al., 1996). The sources of the fluvial and eolian transport systems during the Triassic–Jurassic time have been documented using detrital zircons (Dickinson and Gehrels, 2008a, b). In both eastward and westward subduction models a southwestern source of silicic volcanic debris is generally identified with the postulated Cordilleran arc or Mogollan Highlands (Howell and Blakey, 2013; Riggs et al., 2013, 2016; Dickinson, 2018). Although the active margin, backarc–retroarc models have basin depocenters and syndepositional deformation localized by proximal active compressive and flexural forces of the approaching arc, or slab-related dynamic subsidence, there is ample evidence that much local deformation and localized subsidence was controlled by early Mesozoic halokenesis (salt tectonics) (Shoemaker et al., 1958; Hazel, 1994; Matthews et al., 2007; Trudgill, 2011; Banham and Mountney, 2014; Hartley and Evenstar, 2017) that might, in fact, prove more important than either basement-involved tectonics or eustasy in structuring much of the stratigraphy (P. E. Olsen et al., 2016). An additional, generally overlooked consideration is that the southern and eastern edges of the western US Triassic–Jurassic sequences lie against the projection of the Central Atlantic rift system, and changes in the uplift of the northwestern rift shoulders related to extensional pulses are plausible factors in modulating rates of supply of sediments to the deposits of the American Southwest (Huber et al., 2016).

The more recent history and origin of the Colorado Plateau itself remains somewhat enigmatic and debated as well, with useful recent reviews of the history being Flowers (2010) and Liu and Gurnis (2010). The plateau is characterized by relatively undeformed crust and is almost entirely surrounded by strongly shortened and subsequently highly extended regions. Apparently prior to and after the Late Cretaceous to early Cenozoic formation of the Central and Southern Rocky Mountains, the region was relatively low-lying, but during the medial Cenozoic extension that formed the Basin and Range physiographic province to the west and the Rio Grande rift to the east, the plateau was uplifted by at least a kilometer and originally east-flowing streams and rivers that deeply incised parts of the plateau and reversed their course, resulting in the more modern version of the Grand Canyon of the Colorado River and associated erosional features. The combined effects of the shortening and extension was a clockwise rotation of the Colorado Plateau about a vertical axis of perhaps up to a net $\sim 10^{\circ}$ (see Hamilton, 1981; Steiner, 1986; Kent and Witte, 1993; Bryan and Gordon, 1986; Steiner and Lucas, 2000; Wawrzyniec et al., 2002; McCall and Kodama, 2014). In the late Neogene and Quaternary localized mafic volcanism has taken place, indicating ongoing tectonic evolution of the plateau with the geodynamic origin and timing of the events shaping the plateau remaining hotly debated.

1.3 Climatic context and stratigraphy

In the broadest sense, the stratigraphic sequence on and close to the plateau remained continental to marginal marine through its entire early Mesozoic history. The Colorado Plateau part of Laurentia was near the Equator in the Early Triassic, moved north through the Triassic from more humid latitudes $\sim 7^{\circ}$ at 220 Ma into arid tropics at $\sim 16^{\circ}$ around 200 Ma (close to the Triassic–Jurassic boundary), continued into the arid sub-tropics at $\sim 27^{\circ}$ through the rest of the Early and Middle Jurassic, and then moved into the temperate latitudes $\sim 47^{\circ}$ by ~ 150–140 Ma (and the Jurassic–Cretaceous boundary) and remained approximately at this latitude for nearly 100 Myr (e.g., Kent and Irving, 2010). The plateau and surroundings then moved south to the present latitude of $\sim 37^{\circ}$ (Fig. 4). Apart from the Moenkopi Formation, which remains anomalous in being so "arid-looking" despite being

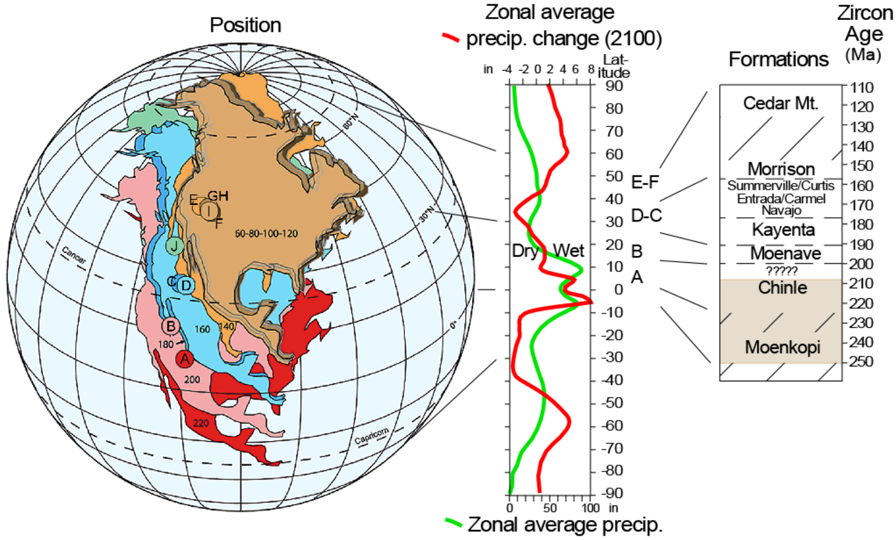

Figure 4. Position of North America (from Kent and Irving, 2010) and the Colorado Plateau (circles) from 220 Ma to Present with comparison to zonally averaged precipitation for today (1950–2000, from https://www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier/, last access: September 2018), change in precipitation for 2100 (ibid.), and the zircon ages for formations (from core CPCP-PFNP13-1A for the Moenkopi and Chinle formations; Suarez et al., 2017 for the Moenave Formation; Marsh et al., 2014 for the Kayenta Formation; Trujillo et al., 2014 for the Morrison Formation; and Mori, 2009 for the Cedar Mountain Formation), with the interval spanned by the CPCP-PNF13 cores shown in tan (hachures indicate hiatuses). This shows how relatively small northward translation of western North America during the Triassic could result in strong changes in climate sensitive facies.

deposited at or near the Equator, the Late Triassic though Cretaceous climate-sensitive sedimentary facies all track latitude, assuming a simple zonal climate (e.g., Kent and Tauxe, 2005), with the giant sand sea of the Early to ?Middle Jurassic age Navajo Sandstone deposited in the subtropics near 30° N, and much less arid facies developing during Late Jurassic and Early Cretaceous times (Fig. 2).

Although characterized by overall very high $p\mathrm{CO_2}$, there are a number of significant fluctuations documented for the Late Triassic (Fig. 2) and Early Jurassic (Schaller et al., 2011, 2015). Although apparently not related to the overall trend in Colorado Plateau climate-sensitive facies, these would be expected to have global change consequences that should be recognizable once the latitudinal shift in the North American Plate is accounted for. At least one of these shifts in the late Norian (Fig. 2) should have been encountered in the CPCP cores.

The oldest Triassic age strata in the PFNP area are part of the nominally Early to Middle Triassic age Moenkopi Formation, its age having been inferred using marine fossils found in distant areas to the west and local tetrapod biostratigraphy (Morales, 1987; Lucas and Schoch, 2002). There are, however, no fossils known from very low in the formation, and therefore its base could conceivably be as old as Late Permian or considerably younger, its top could be as young as early Late Triassic (Carnian) based on admittedly sparse available geochronology (Dickinson and Gehrels, 2009). The Moenkopi could also be of different ages in different areas of the plateau and surroundings. One of the goals of the CPCP is to better constrain the age of these important, paleo-tropical vertebrate assemblages by independent, non-biostratigraphic means.

Most of the rest of Triassic time in the Colorado Plateau is recorded by the continental, largely fluvial Chinle Formation, of which the oldest dated strata are early Norian in age (Olsen et al., 2011; Ramezani et al., 2011) and the youngest late-, but perhaps not latest-Rhaetian in age. The Chinle Formation has provided one of the richest Pangean tropical plant and vertebrate assemblages of Norian and Rhaetian age in the world. In addition, recent advances based on inspection of outcrops have demonstrated that U-Pb detrital zircon geochronology (Ramezani et al., 2011, 2014) provides effective and accurate time control. Putting these outcrop studies in a context where superposition is undoubted, and directly registered to the geochronologic data was another goal of the CPCP.

2 Scientific goals and questions

Based on discussions during the 2007 and 2009 CPCP workshops and preparation for the 2010 proposals, a series of principal guiding questions were recognized. Workshop participants concluded these questions could be best addressed by the environmental and U-Pb calibrated magnetic polarity stratigraphic records of a PFNP core experiment. The questions included the following.

Table 1. Summary data for CPCP drilling sites and cores.

Site	Drill hole	Dates cored	Lat (N)	Long (W)	Elev. (m)	Hole inclination	Azimuth (deg.) dc	Core depth scaled (m)	Core recovery (m)	Stratigraphic depth (m)	Core recovery (%)
Chinde Point	CPCP-PFNP13-1A	11/07/13–11/24/13	35.085933	109.795500	1764	60.2	137.3	519.90	538.10	451.15	103.50
Bone Yard	CPCP-PFNP13-2A	11/27/13–11/29/13	34.822853	109.894091	1711	59.1	200.7	80.77	85.51	69.27	105.87
Bone Yard	CPCP-PFNP13-2B	12/02/13–12/07/13	34.822853	109.894118	1711	75.6	202.9	252.89	262.19	244.95	103.68

1. Is the Newark Basin astrochronostratigraphic polarity timescale (APTS) for the Late Triassic consistent with independent radioisotopic dates and magnetic polarity stratigraphy from the Chinle Formation?

2. Were marine and continental biotic turnover events in the Triassic synchronous? Specifically, as the apparent largest magnitude faunal turnover event on land during the Late Triassic (Mid-Norian, Adamanian–Revueltian boundary) synchronous with the giant Manicouagan bolide impact, independent of it, or an artefact of a condensed section or hiatus, and does it correlate with the marine turnover?

3. There is an apparent pattern of latitudinal biotic provinciality reported in the Late Triassic. Is it supported by high-resolution independent (i.e., non-biostratigraphic) correlations, and is that provinciality correlated with climate-related environmental proxies?

4. Is the orbitally paced (Milankovitch) cyclical climate change recorded in the Newark basin lacustrine facies reflected in the largely fluvial Chinle and Moenkopi formations?

5. Do CO_2 proxies in the western US track those from the eastern US, and how do they relate to the records of environmental change seen in the cores and other areas?

3 Drilling summary

The overall drilling plan was formulated and PFNP was selected as the coring location for Phase One of the project during the 2009 CPCP Workshop at the New Mexico Museum of Natural History and Science in Albuquerque, New Mexico (Geissman et al., 2010). After funding from ICDP was approved in 2010, and from NSF in 2013, the first (Chinde Point) of two specific coring sites was finalized in June and August 2013 after two visits to PFNP to meet with park personnel, representatives of the drilling contractor, and the drilling project manager (D. Schnurrenberger) (Figs. 5 and 6; Table 1). Less than 2 weeks into the coring of the Chinde Point hole, at a depth of over 400 m, it was clear that core recovery through most of the Triassic sequence was excellent and progressing at a rapid and very successful rate. It quickly became clear that we would finish ahead of schedule and under budget. Consequently, we requested a small amount of additional funding from ICDP to leverage our setup to core a second site, which was approved in late November (Figs. 5 and 6; Table 1). The rational for a second coring site in the southern part of the park was that it would allow us to assess the lateral variation and completeness in physical and paleomagnetic polarity stratigraphy. Site 2 selection commenced immediately and set up and coring at site 2A began on 26 November 2013 (Fig. 5), with the planned total depth of core

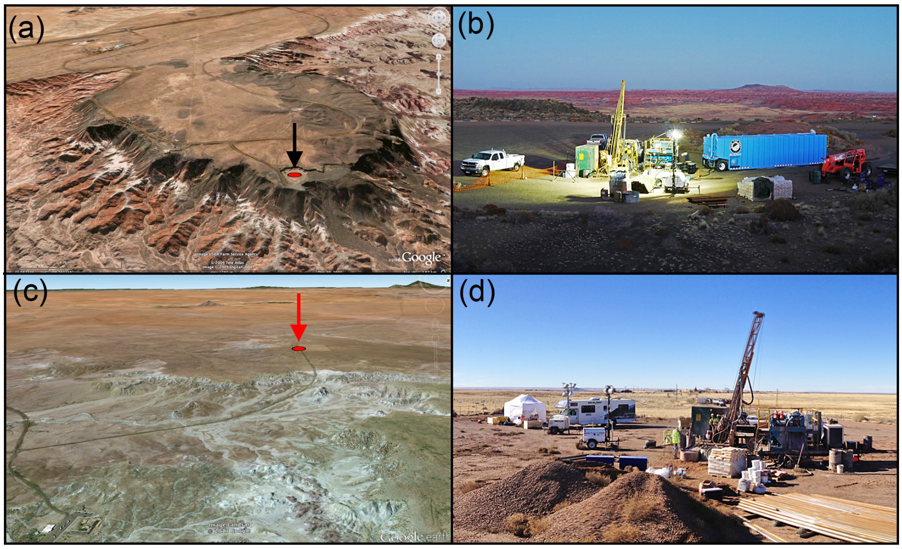

Figure 5. CPCP coring sites: **(a)** Chinde Point (GoogleEarth image) looking south with CPCP-PFNP13-1A coring site in the foreground (red dot and arrow) on mesa capped by Bidahochi Formation lava and lake strata overlying basal Owl Rock Member and Petrified Forest Member of the Chinle Formation with the prominent white band being the ash-rich Black Forest Bed of the upper Petrified Forest Member – Park Headquarters is at upper left; **(b)** CPCP-PFNP13-1A coring site at Chinde Point, looking north at dusk, during coring; **(c)** "West Bone Yard" (GoogleEarth image) site of CPCP-PFNP13-2A and -2B (red dot and arrow) looking west – hills in the distance are Hopi Buttes Bidahochi Formation mares and buildings in the foreground; left are parts of the Rainbow Forest Museum; **(d)** CPCP-PFNP13-2B site at "West Bone Yard" during coring, looking west.

1A (bottoming in Early Permian age Coconino Sandstone) having been reached on 24 November 2013. Site 2A was terminated on December 2 because of problems with hole collapse, and the rig was moved over about 4 m and coring at site 2B commenced on 2 December and total depth was reached on 7 December 2013 (again bottoming in Early Permian age Coconino Sandstone) (Table 1). The additional core processing and associated science for these two additional cores required a supplement from NSF that was approved in December 2015.

Ruen Drilling, Inc. was the coring operator, having also been the operator for the Bighorn Basin Coring Project (BBCP) in very similar lithologies (Clyde et al., 2013). As was the case for the BBCP, a truck-mounted Atlas Copco CS1500 wireline diamond coring rig, with HQ3 tooling was used to recover the cores (6.1 cm diameter) in polycarbonate liners. Liners were used because of the extremely crumbly nature of the Chinle mudstones that have long been known to have a high expanding clay component of probable volcanic origin (e.g., Allen, 1930; Schultz, 1963). As coring proceeded it became obvious that without liners, recovery in the mudstones (comprising a large proportion of the section) would have been substantially reduced and/or disrupted by drilling and core handling, rendering such cores much less useful for high-resolution analyses and scans. Drilling fluids were water, with minimal additives similar to those used by the BBCP (for core BBCP-PCB11-2B), specifically bentonite powder, polymer, and soda ash due to the necessity of an inclined corehole to avoid rod damage and hole collapse (core hole PFNP13-2A was in fact abandoned because of hole collapse). An AMC Solids Removal Unit centrifuge extracted the cuttings from the drilling fluid during drilling, allowing fluid recycling and cuttings disposal off-site.

Core handling and documentation were led by D. Schnurrenberger and members of the NSF LacCore/CSDCO facility (K. Brady and R. O'Grady), who served as a drilling-science liaison ("company representative") while working on opposite shifts and with support of the science team. After coring, the holes were logged by Century Wireline Services (CWS) (Fig. 5). Down-hole logs were taken to virtually the bottom of holes 1A and 2B, and included magnetic susceptibility, natural gamma ray, resistivity, spontaneous potential, acoustic borehole imaging, and dipmeter surveys, the latter of which are consistent with the Reflex EZ Shot survey data, used to track orientation of the hole during drilling. After logging the holes were filled with heavyweight mud and sealed with cement near the surface.

Because the paleomagnetic polarity stratigraphy of the cores was an essential part of the project, core azimuthal orientation was critical, and we employed three strategies towards that end. First, because bedding is nearly flat in PFNP, the core holes were planned to deviate from vertical, inclining 60° or 75° to the SE or SSW depending on the core (Table 1). Inspired by Baag and Helsley (1974) in core recovered from the Moenkopi Formation of Colorado, this allows bedding, or some physical proxy of bedding, to serve for core

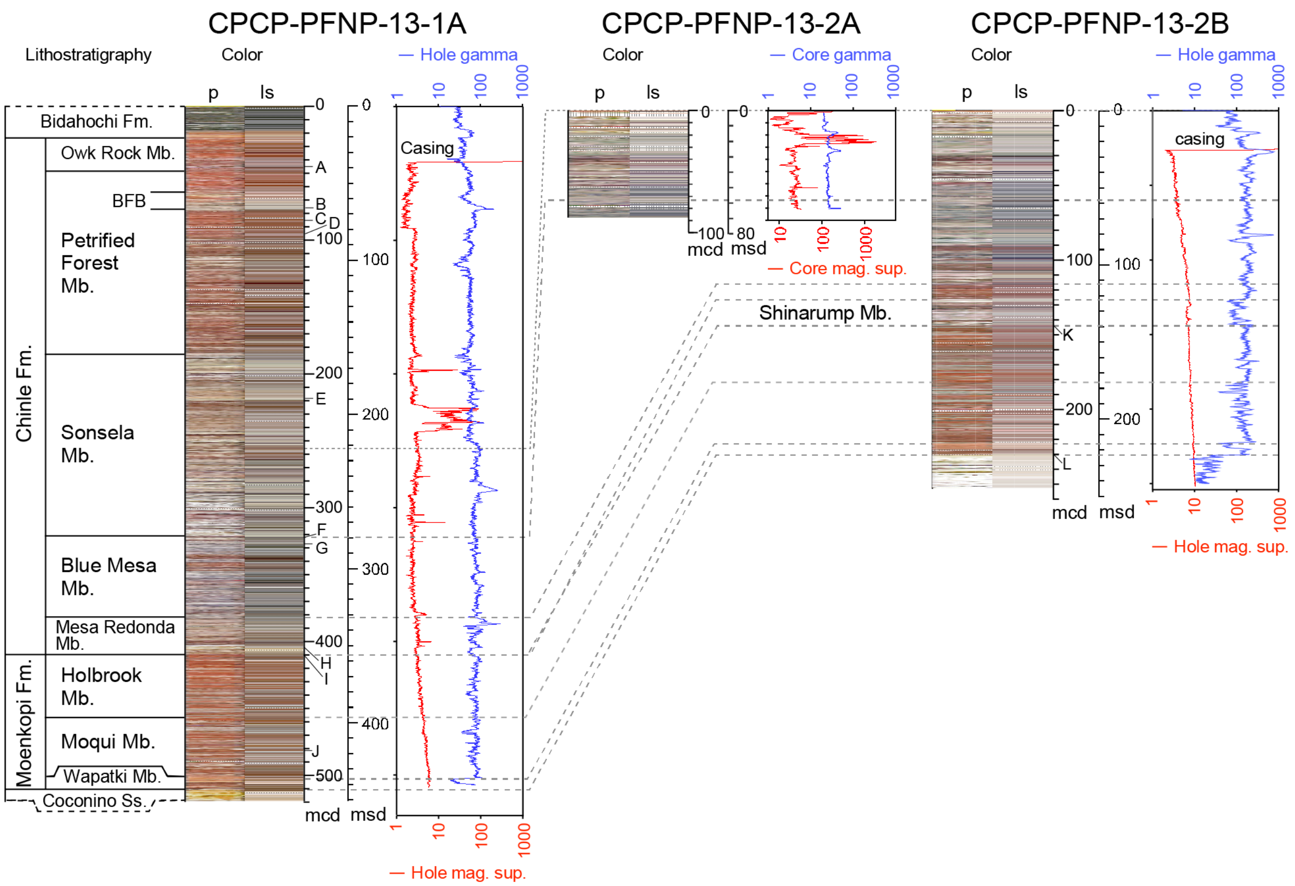

Figure 6. Lithologic logs, compressed photographs (p), line-scan images (ls), natural gamma, and magnetic susceptibility, for each of the cores and holes drilled during the CPCP. Letters A–K refer to core segment photographs in Fig. 8. Abbreviations for the core depths are mcd, meters core (or hole) depth; msd, meters stratigraphic depth of a core or hole with msd = 0.866 · mcd in 1A, msd = 0.858 · mcd in 2A, and msd = 0.969 · mcd in 2B.

orientation (Fig. 7). This was necessary because during the Triassic the Colorado Plateau was at low latitudes as indicated by paleomagnetic inclinations being close to horizontal (e.g., Molina-Garza et al., 1991) meaning that the polarity could not be assessed from inclination values alone. Second, core orientation was tracked using a REFLEX ACT II/III tool that employs an accelerometer to record the core orientation, with the down side of the inclined hole being marked on the bottom core surface after each run based on the device's data. That mark was then extended to the core liner as a white line marked down the entire length of the liner (or core). A similar tool was used at the Hominin Sites and Paleolakes Drilling Project (HSPDP) (Cohen et al., 2016). Third, after drilling ended, cores 1A and 2B were CT-scanned in their entirety at the University of Texas at Austin's CT-Scanning US NSF Facility (Fig. 8), to assure that we would have images to check bedding, which we could not see through the transparent plastic liners because of the opacity of the drilling mud, colored by the red beds. These scans will also provide a wealth of three-dimensional sedimentologic details otherwise not visible (Fig. 8). The nominally 1.5 m core runs were cut on site into roughly 0.7 m (actual average of 71 cm) segments so that they would fit into the CT-Scanner (not to exceed 76.2 cm). The up/down orientation of the core segments is maintained with blue endcaps on tops and red endcaps on bottoms of liners, hand-drawn arrows marked on the plastic tube pointing up-core, and T (top) and B (bottom) labels near the endcaps.

The PNFP cores were labeled and cataloged in the field by Schnurrenberger, Brady, and O'Grady, with support from the science team, and were named using the LacCore convention, which is an extension of the IODP and ICDP syntax. For this project, the naming convention is as follows, using CPCP-PFNP13-1A as an example: CPCP, is the expedition name (Colorado Plateau Coring Project); PFNP, is the overall location (Petrified Forest National Park); 13, is the year drilled (2013); 1, is the coring site (site 1, at Chinde Point); and A, is the hole at site (in this case only 1 hole). The cut core segments are labeled continuing with the LacCore protocol, for example for CPCP-PFNP13-2B-108Y-1-A: 108, is

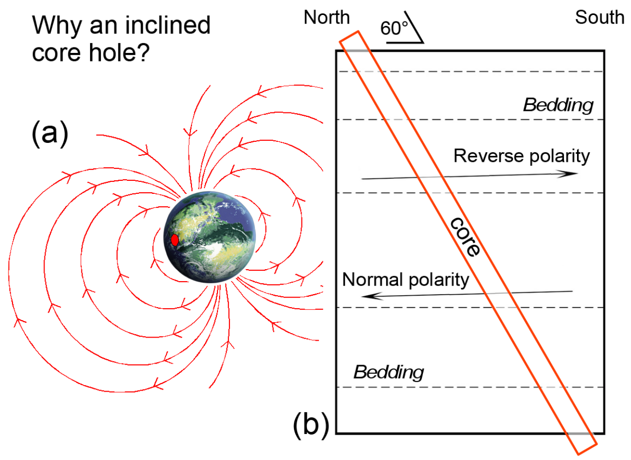

Figure 7. The nearly horizontal bedding in PFNP was used for orientation by inclining the corehole nominally 60° for 1A and 2A and 75° in approximate southerly directions (see Table 1). **(a)** Earth's magnetic field line (normal polarity) with Earth with Triassic Pangea and location of Colorado Plateau (red dot) – note the field lines near horizontal near the Equator. **(b)** Diagram of inclined core hole at 60° with normal and reverse polarity field lines near horizontal due to low latitude position of the Colorado Plateau during the Triassic. The cores were intended to be split along the perpendicular to the inclined core so that bedding is seen to dip 30° , for 1A and 2A, or 15° for 2B, relative to the long axis of the core (compare with Fig. 8).

the core barrel run (run 108); Y, is the code for the coring tool used; 1, is the core segment (uppermost segment cut off the core run); and A, is the designation of the archive half (with W, designating the working half. This code applies to all of digital descriptive data as well (e.g., digital photographs).

3.1 Site 1: Chinde Point

Chinde Point, in the northern part of the PFNP (Fig. 5; Table 1), was selected as the main site (for CPCP-PFNP13-1A) because the zircon U-Pb dated Black Forest Bed (Riggs et al., 2003; Ramezani et al., 2011) outcrops directly adjacent to the site providing an important fiducial, and it allows for coring the highest stratigraphic level in the Chinle Formation accessible using a truck-mounted rig. The location picked also consists of an easily accessible parking lot in the floor of an old barrow pit that could be drilled into thus minimizing disturbance – a key consideration of the Park. Total depth was 519.9 m yielding a total stratigraphic depth of 451 m (Table 1).

Chinde Point is on the northern edge of a mesa capped by Miocene ($\sim$ 8.7–6 Ma) "middle" Bidahochi basalt flows of the Hopi Buttes volcanic complex (White, 1990), into which core 1A was spudded. The basalt is underlain by "lower" Bidahochi gypsiferous Neogene (Miocene) lacustrine pale red mudrock, which locally overlies the Triassic age section. The knowledge that there is a remnant of a possible

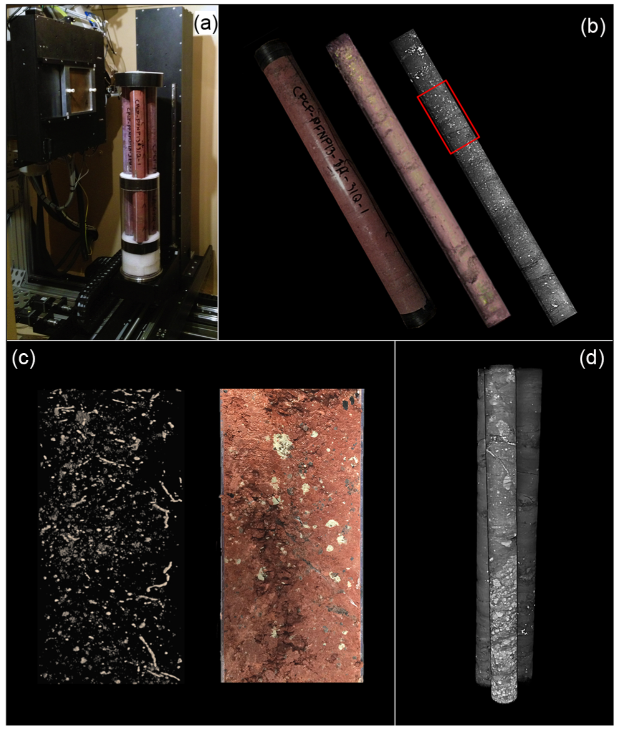

Figure 8. CT scans of CPCP-PFNP13-1A core: **(a)** three core segments bundled with aluminum rod at center in the 450 kV GE Titan X-ray source and Perkin Elmer flat-panel detector at the University of Texas High Resolution X-ray CT Facility, Austin, TX – visible in the front is CPCP-PFNP13-A1-31Q-1 (cores are approximately 0.7 m long); **(b)** four images of core segment CPCP-PFNP13-A1-31Q-1 at core depths 37.5 to 38.2 m is equivalent to 32.5 to 33.1 m stratigraphic depth in the basal Owl Rock Member of the Chinle Formation (left image is in visible light with core in its liner, middle image is a colorized CT volume with liner digitally stripped off; right image is a CT volume with an addition 2 mm stripped off to digitally clean off drilling mud – red box is interval shown in **c**); **(c)** enlargement of CT volume shown in red box in **(b)**, left image is CT volume filtered to highlight carbonate-rich rhizoliths (root traces) and right image is digital photograph of the same interval in the slabbed core (core is $\sim$ 6.35 cm in diameter) (see https://www.youtube.com/watch?v=T05S7R7dP7M, last access: September 2018); **(d)** bundle of three core segments of Owl Rock Member of the Chinle Formation from CT animation of CPCP-PFNP13-1A-25Q2 (foreground); CPCP-PFNP13-1A-26Q2; CPCP-PFNP13-1A-27Q1 with CPCP-PFNP13-1A-25Q2 volume showing conglomerate and clear bedding inclined to left (cores are approximately 0.7 m long) (see https://www.youtube.com/watch?v=ynM-H8_Qu7A&feature=youtu.be, last access: September 2018).

vent (Ouimette, 1992) on the northwestern side of the mesa only 700 m southwest from the drill site, and that the vent and lavas might be the remnants of a maar with associated faults, stocks, and phreatic breccias, prompted us to select an azimuth of $\sim$ 135° (Table 1) as opposed to due south, which would be more nearly optimal from a paleomagnetic perspective. Fortunately, no such features were intersected by the core, and there is no obvious magnetic overprint of Miocene age (Kent et al., 2018), and therefore we conclude the strata recovered in this core were minimally affected by the Neogene igneous activity.

Triassic rocks encountered in PFNP13-1A comprised 335 m of Late Triassic (Norian) Chinle Formation mudstones, sandstones, and conglomerates that overlie 88 m of nominally Early and Middle Triassic age Moenkopi Formation. The hole reached a total depth of 451.0 m after penetrating 7 m of Early Permian age Coconino Sandstone (Fig. 6: Table 3) (in stratigraphic thickness all rounded to the nearest meter). The recovered core represents the first time both the lower and upper parts of the Chinle Formation, as can be seen in the area of the PFNP, can be inspected and sampled in undoubted superposition.

3.2 Site 2: West Bone Yard

To leverage the new information from coring at Chinde Point, site 2 was selected to be in the southern part of the park, about 30.6 km from site 1. Initially, we had hoped to site it about 2 km farther to the east, which would have been at a higher stratigraphic position; however, the weather conditions did not permit the drilling truck and support equipment to access that area. Instead we drilled in an equipment storage area called the "West Bone Yard", again minimizing additional disturbance. Unlike the Chinde Point site, bedrock drilling commenced immediately in Triassic strata. Two cores were acquired at site 2: CPCP-PFNP13-2A and CPCP-PFNP13-2B. Our intention was to again core at an inclination of about 60°. However, coring of PFNP-2A (inclined at $\sim 60°$) was terminated at a total depth of 81 m (69 m stratigraphic depth) because of hole collapse, and we decided to site PFNP13-2B about 3 m to the west and drill at an inclination of about 75° for the entire hole (Table 1). Far fewer problems were encountered coring PFNP13-2B and total depth was reached at about 253 m, comprising about 245 m of stratigraphic section (Table 1). Despite the shortness of core PFNP13-2A, it duplicates the upper part of the Chinle in PFNP13-2B and thus provides a useful replicate, complementing the minor core loss in both cores.

Core PFNP13-2B spans more than one-quarter of the section recovered at Chinde Point (a total of about 144 m), but it is invaluable because it is adjacent to the most data-rich parts of the park sequence. Approximately 87 m of the Moenkopi Formation was cored along with 22 m of Coconino Sandstone. Therefore, data from core PFNHP13-2B will permit clear calibration of the fidelity and completeness of the lower Chinle and Moenkopi sections.

4 Core analysis and initial post-drilling science

From PFNP, the cores were shipped to The University of Texas at Austin High-Resolution X-ray Computed Tomography Facility (UTCT). There the cores were scanned on the high-energy subsystem of the North Star Imaging scanner. This subsystem employs a 450 kV GE Titan X-ray source and a Perkin Elmer flat-panel detector. These data were acquired at 355 kV and 1.5 mA, and four brass X-ray prefilters were employed. The detectors were binned 2×2, resulting in a voxel size of 0.1825 mm. Depending on the length of the core segments, the scanning protocol used helical or cone-beam acquisition or a combination of the two; most core segments required the latter, with resulting volumes digitally stitched together. The core segments were scanned in groups of three, with an aluminum rod placed between them to reduce CT artifacts and provide a greyscale calibration standard (Fig. 8). All cores were labeled with aluminum tags stamped with the core identifiers, and affixed to indicate coring orientation. The final data volume comprises 394 CT data sets ranging from 299 to 4330 16 bit TIFF slices.

After CT scanning the cores were shipped to the LacCore facility at the University of Minnesota for Initial Core Description (ICD). Facility staff passed the cores through a Geotek MSCL-S multisensor core logger, for standard parameters: magnetic susceptibility, gamma density, P-wave velocity, electrical resistivity, and natural gamma radiation. Cores were subsequently split in half lengthwise with a rock saw plumbed for continuous deionized water flush (no recirculation) and cleaned. One-half of each core was photographed with a Geotek MSCL-CIS optical linescan camera at 50 micron resolution, and then logged on a Geotek MSCL-XYZ split-core multisensor logger for high-resolution magnetic susceptibility and color reflectance spectrophotometry. Visual lithologic core descriptions were generated by project staff using PSICAT software and modified FGDC standard vocabularies for lithologies, with petrographic smear slide analysis, SEM-EDS, and XRD analyses as needed for component identification. A subset of core archive halves (Petrified Forest and upper Sonsela members) were scanned using an ITRAX XRF Core Scanner for elemental distributions. Scanning of the rest of the cores is anticipated during 2018. The cores remain the property of the US Federal Government (with PEFO (PFNP) catalog numbers: core 1A is PEFO 39602; core 2A is PEFO 39603; core 2B is PEFO 39604); the cores are on long-term loan with all archive halves permanently curated at the LacCore/CSDCO core repository and working halves curated at the Rutgers University Core Repository for subsampling, and additional detailed descriptions.

The LacCore/CSDCO facility coordinates access to core archive halves and fundamental data; Rutgers University coordinates access to core work halves for subsampling. Fundamental datasets include core metadata, multisensor logger data, core photographs, lithologic core descriptions, XRF elemental scans, and derived products such as color profiles and stratigraphic columns. Depth scales were standardized by LacCore/CSDCO, using scaled meters below surface (applying a linear compression/scaling where recovery is above 100 %), equivalent to the CSF-B depth scale used in IODP.

The initial sampling party for core 1A was held on 17–20 April 2015 at the Rutgers Core Repository with samples being taken for paleomagnetic analysis, U-Pb geochronology, carbon isotope stratigraphy and soil carbonate CO_2 proxy, palynology and organic geochemistry (compound-specific C isotopes, $\delta^{13}C_{wax}$), by the lead National Science Foundation PIs and their coworkers along with several additional scientists. Individual teams have sampled and will continue to sample core 1A as needed. Sampling parties for cores 2A and 2B, recently processed by at UTCT and LacCore (funded by a supplement from NSF), took place during spring 2018.

5 Initial results

A basic result evident from the stratigraphy of core PFNP13-1A is that the major discrepancies between the stratigraphy and thickness estimates of Chinle Formation sections in Petrified Forest National Park, as reported by various workers due to the large geographic distances between outcrops where superposition cannot be demonstrated, can now be resolved. The stratigraphy and thicknesses of the major members in core 1A (Fig. 6) closely approximate those of Martz and Parker (2010), Ramezani et al. (2011), and Atchley et al. (2013) and are dramatically different from those depicted by Billingsley (1985), Murry (1990), Steiner and Lucas (2000), and Heckert and Lucas (2002). It can thus serve as a standard lithostratigraphic reference for most of the Late Triassic age continental rocks of the Colorado Plateau. In terms of depositional environments, the Chinle strata in the cores are almost entirely comprised of muddy fluvial paleosols and coarser fluvial channel deposits (Fig. 9).

Overall, there is perhaps a surprising degree of agreement in the lateral consistency of facies between the 1A and 2B cores as evident in the geophysical logs, especially natural gamma (Fig. 6). There is variability between the alternations of mudstone and sandstone in the Sonsela Member, but nonetheless, details of log character persist across the ~ 31 km separating the cores. There are also negligible thickness differences between the lower Chinle strata in the cores, despite the change in facies in the basal-most part of the formation. Supposedly, the conglomeritic facies of the basal Chinle Formation, traditionally referred to as the Shinarump Member, occupies incised valleys in the underlying Moenkopi, but that is not at all evident in core 2B, which contains that conglomerate (clasts up to medium cobble size), and 1A, which does not and the Shinarump is simply replaced by finer-grained facies of the Mesa Redondo Member lying directly on top of the Moenkopi Formation (Fig. 9). The Moenkopi Formation itself is nearly exactly the same thickness in core 1A and 2B, and also shows a strong similar consistency in the log properties of the members of the formation, most notably in the Moqui Member (Fig. 5).

However, there is a major consequential difference between the outcrops in the park and what is seen in the cores. There is a complete absence of facies resembling the Newspaper Rock Sandstone and attendant low-energy well-bedded mudstones and siltstones in all the cores. These strata comprise large, sandstone, meandering channel complexes up to 10 m thick with large-scale greenish lateral accretion sets making up scroll bars (ridge-and-swale topography) visible in satellite images. The lateral accretion sandstones have basal lags with abundant fossil wood and plant impressions, and there are associated lacustrine deposits (Trendell et al., 2013) that yield a diverse aquatic fauna and macro- and micro-flora (Daugherty, 1941; Miller and Ash, 1988; Ash, 1989, 2005; Murry and Long, 1989; Demko, 1995; Heckert, 2004; Parker, 2006; Parker et al., 2006a). Very similar facies have been described at various areas of outcrop of the Chinle Formation and have been collectively termed the "Monitor Butte facies", ascribed to incised valleys (Demko et al., 1998). These facies only outcrop locally even in the park and in most areas it they are represented by a laterally continuous red band of pedogenically modified strata about 1 m thick. However, in several areas outside the park such "incised valleys" appear related to underlying halokinesis of Paleozoic salt (Matthews et al., 2007; P. E. Olsen et al., 2016). Such strata are often characterized by extraordinarily fast accumulation rates as evidenced by the burial of in situ plants, including trees (Parker et al., 2006b; Trendell et al., 2013) implying rates of several meters in a few years (Fig. 10), which would be highly problematic for interpreting paleomagnetic polarity sequences, had this facies occurred in the cores. The southern part of the PFNP in fact lies directly on the center of the thick evaporites of the Holbrook Basin (Rauzi, 2000), making halokinesis a plausible cause of localized development of the Monitor Butte-Newspaper Rock facies.

Outcrops of the Chinle Formation at Petrified Forest National Park have provided much of the basis for our understanding of the palynostratigraphy of the American Southwest Late Triassic (Gottesfeld, 1972; Scott, 1982; Fisher and Dunay, 1984; Litwin et al., 1991; Reichgelt, et al., 2013; Whiteside et al., 2015; Lindström et al., 2016). In total, 258 samples were collected from core CPCP-PFNP13-1A for palynological, bulk C-isotope, and $\delta^{13}C_{wax}$. Of these about thirty samples were processed at the University of Oslo and all were barren of recognizable sporomorphs, although very dark, degraded woody or cuticle-like plant fragments are present, consistent with recalcitrant soil organic matter in paleosols (Fig. 11). The prevalence of red and purple paleosols and the lack of "Newspaper Rock-Monitor Butte facies" are at least partially responsible for the near lack of organically preserved plant macrofossils and sporomorphs from the core. Samples were processed for organic geochemistry at Utrecht University (NL) following the methods outlined in Miller et al. (2017). Results indicate very low concentrations of *n*-alkanes which did not have the odd-over-even carbon prefer-

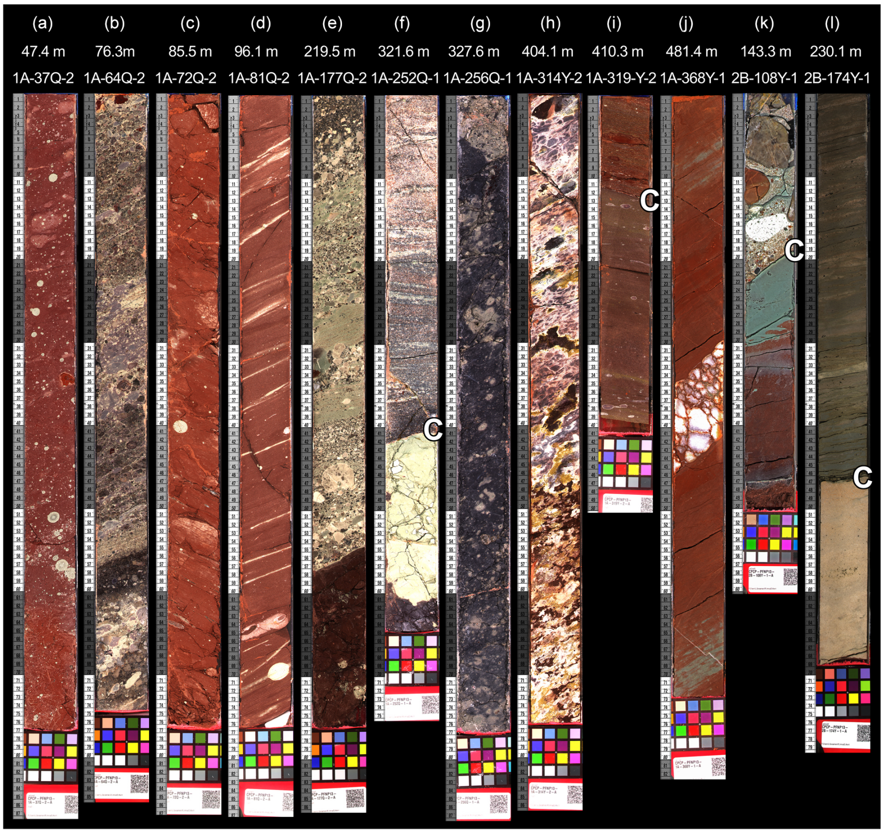

Figure 9. Representative facies in core segments from cores CPCP-PFNP-13-1A **(a–j)** and CPCP-PFNP-13-2B **(k–l)** with bedding dipping down towards left except as noted (see Fig. 5): **(a)** pedogenic mudstone of lower Owl Rock Member of the Chinle Formation in which bedding is obscure but indicated by long axes of elliptical spots ("reduction spots or haloes"); **(b)** lower Black Forest Bed of the Petrified Forest Member of the Chinle Formation with abundant intraformational carbonate clasts and volcaniclastic material; **(c)** pedogenic mudstone of the Petrified Forest Member of the Chinle Formation with long axis of elliptical spots inclined downward to the right indicating a misoriented core segment; **(d)** pedogenic ripple-bedded fine sandstone and siltstone of the Petrified Forest Member of the Chinle Formation with long axes of elliptical spots clearly aligned with bedding; **(e)** sandstone and conglomerate overlying pedogenic mudstone within the upper Sonsela Member of the Chinle Formation; **(f)** Contact C between coarse sandstone of the overlying Sonsela Member of the Chinle Formation and the underlying Blue Mesa Member of the Chinle Formation; **(g)** pedogenic mudstone of the Blue Mesa Member of the Chinle Formation; **(h)** four-color mottled pedogenic mudstone of the Mesa Redondo Member of the Chinle Formation; **(i)** Contact C between sandstone of the overlying Mesa Redondo Member of the Chinle Formation and sandstone and siltstone of the underlying Holbrook Member of the Moenkopi Formation (core segment appears misoriented); **(j)** chicken-wire gypsum bed in siltstone of the Moqui Member of the Moenkopi Formation; **(k)** Contact C between cobble conglomerate of the overlying Shinarump Member of the Chinle Formation and sandstone and siltstone of the underlying Holbrook Member of the Moenkopi Formation; **(l)** Contact C between sandstone of the overlying Wupatki Member of the Moenkopi Formation and sandstone of the underlying Coconino Sandstone of Early Permian age.

ence typical of waxes derived from vascular plants as can be seen in rocks of comparable age elsewhere (Fig. 12) (Whiteside et al., 2010). These results are unsurprising in as much as the samples also lacked sporomorphs and well-preserved cuticles. The extracted n-alkanes may be indigenous, sourced from pedogenic bacteria or fungi, or the result of biomass burning (e.g., Kuhn et al., 2010; Eckmeier and Wiesenberg, 2009). They could also be natural migrated hydrocarbons. Hydrocarbon shows have been reported in drill holes in the region around PFNP, presumably derived from marginally mature, marine sources rocks in the underlying Paleozoic age Holbrook Basin (Heylmun, 1997; Rauzi, 2000; Schwab et al., 2017). Furthermore, there is also a remote possibility of an n-alkane contribution from drilling fluid additives, although their effect should be minimal because of standard sample preparation protocols. The lack of n-alkanes derived from higher plants and the very low concentrations of indigenous organic matter within the samples meant that further organic geochemical, bulk C isotope and sporomorph, studies were not pursued by WMK, CM, and VB. Nevertheless, additional work on the organic petrology and geochemistry is planned by others.

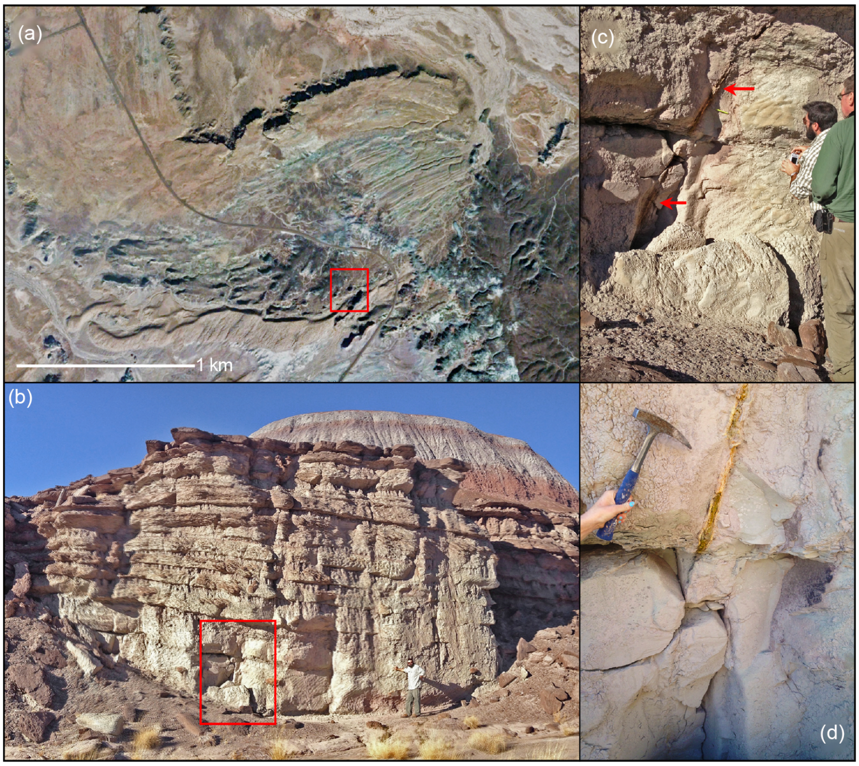

Figure 10. Details of Newspaper Rock facies which is absent in cores: **(a)** GoogleEarth image of scrollbars (best developed in middle of image), red box is location of photo in **(b)**; **(b)** tilted beds of greenish ripple-crosslaminated sandstone and siltstones looking north at scrollbar (point bar) at 34.949°, −109.776° with +2 m upright, plant stem (?*Equisetities*) in growth position in red box enlarged in **(c)** indicative of extremely fast accumulation (∼ +1 m/season) – Morgan Schaller for scale; **(c)** plant stem (?*Equisetities*) in growth position (portion between arrows) is enlarged in **(d)** – beds dip from right (west) to left (east) with faint left-inclined streaks being aligned lee faces of climbing ripples; **(d)** close up of stem in growth position, hammer is 28 cm long – yellow color is due to weathered pyrite.

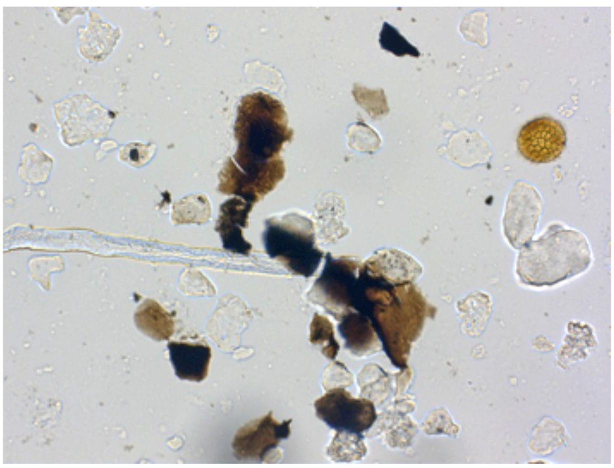

Figure 11. Photograph showing organic residue with degraded cuticle, charcoal, and wood fragments. Identifiable sporomorphs are modern *Lycopodium* spores added to calibrate abundances during palynological preparation.

As planned, the CPCP cores provide a venue for answering the major questions posed at the start of the project. Although work on these cores is still in its early stages, we can report some results and work in progress that address the questions set out during the project's origin as follows.

1. Is the Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) for the Late Triassic consistent with independent radioisotopic dates and magnetic polarity stratigraphy from the Chinle Formation? Thus far, we have been able to recover magnetostratigraphic polarity sequences from the full middle Sonsela through the entire Petrified Forest members of the Late Triassic-age Chinle Formation (40–240 msd) (Kent et al., 2018). Young euhedral detrital zircons apparently largely representative of the depositional age were identified in 29 out of 41 levels in core 1A surveyed using the LA-ICP-MS US NSF Facility at the University of Arizona, with about 100 to >300 crystals being dated in most samples. Of these, the youngest populations of the same zircons of 10 samples were selected thus far for CA-ID-TIMS dating

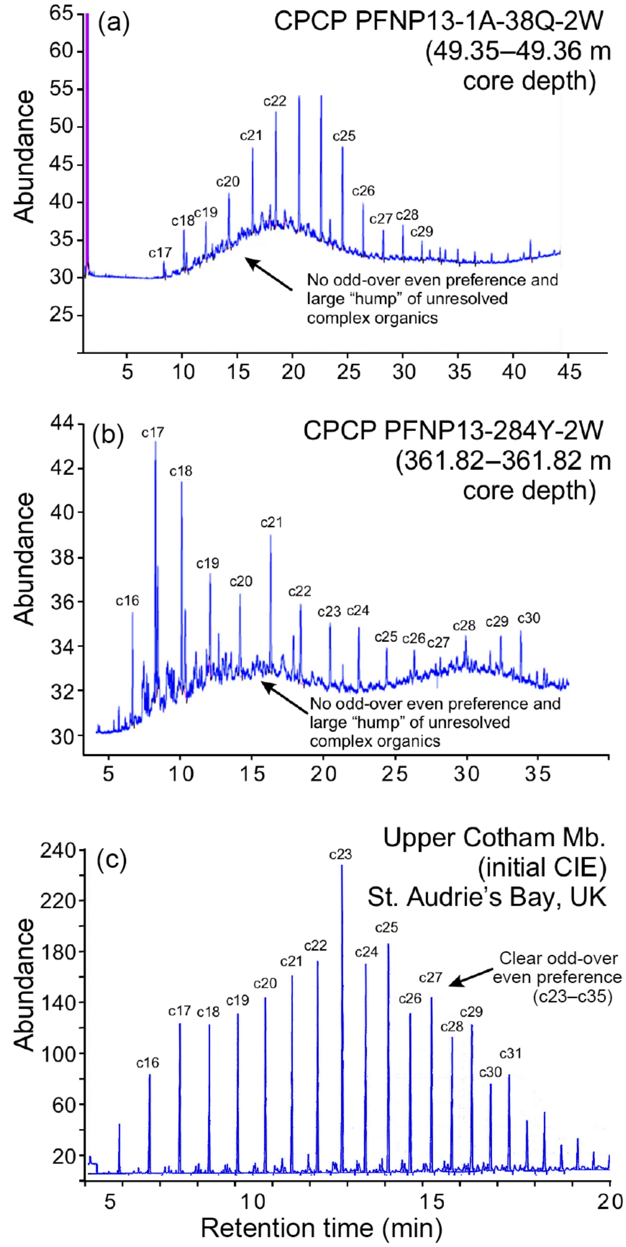

Figure 12. GC chromatogram traces for n-alkanes of the saturate fractions of the extracts from PNFP core samples. **(a)** Trace of CPCP PFNP13-1A-38Q-2W 47–48 cm in the Petrified Forest Member (= 49.35–49.36 m core depth) from detector 1, showing no odd-over-even preference of n-alkanes and a large hump of unresolved organic compounds, possibly due to organic degradation during pedogenesis or because the samples were too thermally mature. **(b)** Trace of CPCP PFNP13-1A-38Q-2A-284Y-1W 65–70 cm in the Blue Mesa Member (= 361.82–361.82 m core depth) from detector 1, showing low abundance of organics, and mostly short chain n-alkanes characteristic of migrated, mature hydrocarbons. **(c)** Trace of the latest Rhaetian age upper Cotham Member, St. Audrie's Bay, Somerset, UK, with the δ^{13}C initial excursion of Hesselbo et al. (2002) from Whiteside et al. (2010).

at the Berkeley Geochronology Center yielding maximum depositional ages in stratigraphic order, within error four of which are published (Figs. 13 and 16). For the Chinle Formation these ages are consistent with published CA-ID-TIMS ages from outcrops in PFNP (Ramezani et al., 2011, 2014; Atchley et al., 2013). Of the new CA-ID-TIMS ages, four are registered to the Chinle magnetic polarity sequence from core 1A. The zircon-calibrated Petrified Forest and upper Sonsela member magnetostratigraphy fully validates the Newark-Hartford APTS, and answers the first major question addressed by the CPCP (Fig. 13) (Kent et al., 2018). It is important to note that correlation of the Newark-Hartford APTS with marine Tethyan strata resulted in a major revision to the duration of the divisions of Late Triassic, with the duration of the Norian Age increasing from 11–14 Myr (Gradstein et al., 1994; Ogg, 2004, 2012; Lucas, 2018) to 21 Myr (Kent et al., 2017a), making it the longest age (stage) of the Phanerozoic. It also had the consequence of showing that the lower half of the Chinle Formation (of Adamanian Age) that was formerly regarded as Carnian (e.g., Lucas et al., 1993, 1998, 2010) is in fact Norian in age (Olsen et al., 2011). Based on these results we can show that a globally exportable timescale can be developed from cores of these types of continental strata. In addition, paleomagnetic and magnetic anisotropy data have been developed for all of the Moenkopi Formation in PFNP13-1A (Buhedma et al., 2016; Buhedma, 2017; McIntosh et al., 2017) (Figs. 14 and 15), and this CA-ID-TIMS zircon calibration of this sequence will provide an independent assessment of how faunal assemblages from this formation fit into the global recovery from the Permo-Triassic mass extinction. We anticipate working out the rest of the magnetostratigraphy in cores PFNP13-1A and in -2A and -2B, during 2018.

2. Were marine (Onoeue et al., 2016) and continental biotic turnover events in the Triassic synchronous? Specifically, was the apparent largest magnitude faunal turnover event on land during the Late Triassic (Mid-Norian, Adamanian–Revueltian boundary; Parker and Martz, 2011) synchronous with the giant Manicouagan bolide impact (Ramezani et al., 2013; Olsen et al., 2011), independent of it, or an artefact of a condensed section or hiatus, and does it correlate with the marine turnover? No certain representation of the "persistent red silcrete" that acts as a local stratigraphic marker of the Adamanian–Revueltian boundary in the southern part of the park was identified in the core 1A. This is not surprising because the "persistent red silcrete" occurs only in a very limited area in the northern area of the park and its possible equivalent, Billingsley's (1985) "brown sandstone" (Parker and Martz, 2011) has not

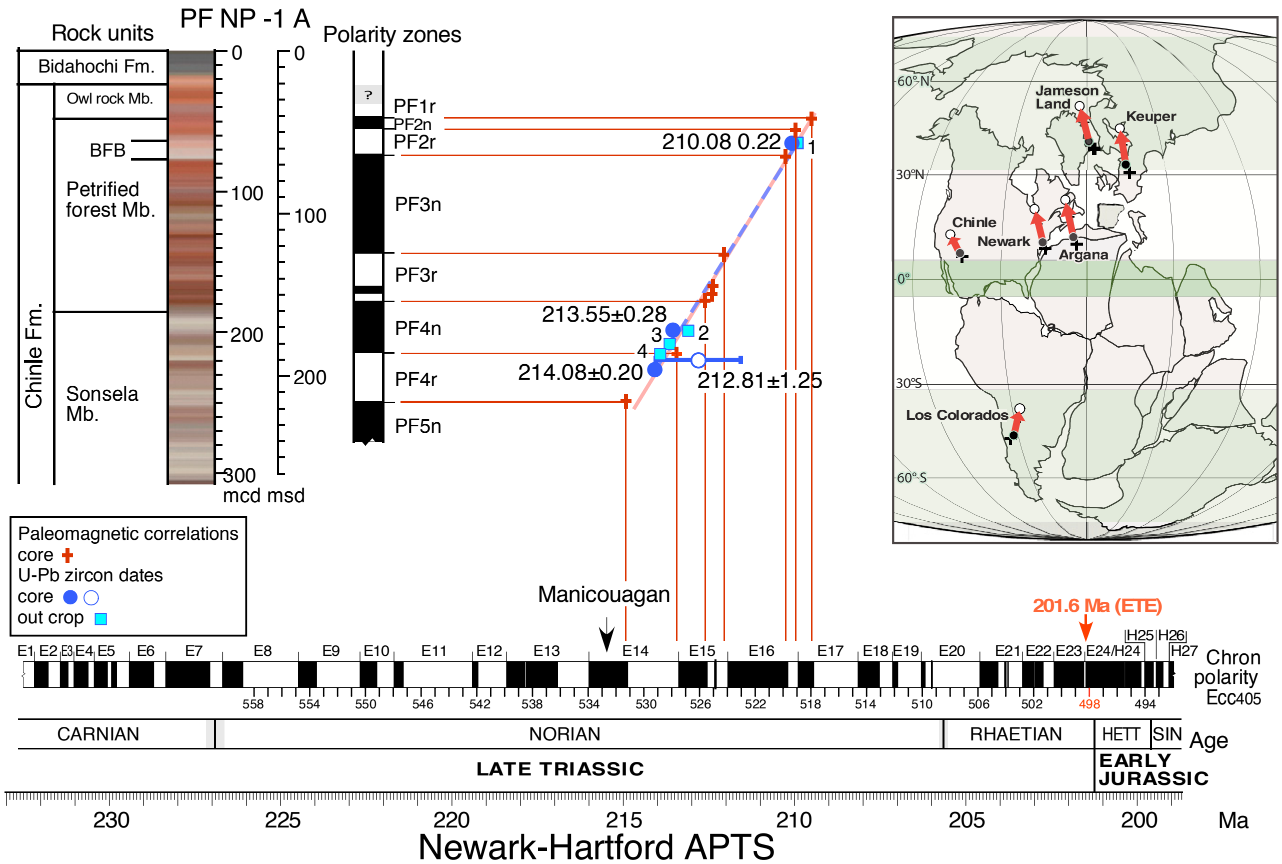

Figure 13. Depth versus age plot for core CPCP PFNP13-1A based on correlation of magnetostratigraphy with the Newark–Hartford APTS (from Kent et al., 2018). Stratigraphic units, graduated depths, and color log of CPCP PFNP13-1A. Red crosses are magnetozone boundaries in CPCP PFNP13-1A; correlated with the NH-APTS solid red line is a linear regression for base magnetozone PF1r to base magnetozone PF4r to their correlative chronological ages. Blue circles are U-Pb CA-ID-TIMS detrital zircon dates from CPCP PFNP13-1A; light blue squares are published U-Pb CA-TIMS detrital zircon dates from outcrop (from Ramezani et al., 2011; Atchley et al., 2013): 1, 209.93 ± 0.07 Ma; 2, 213.12 ± 0.07 Ma; 3, 213.63 ± 0.13 Ma; 4, 213.87 ± 0.08 Ma. Linear regression on U-Pb ID-CA-TIMS dates (blue dashed line) based on sample data from core CPCP PFNP13-1A (excluding sample 177Q1); and light red line is regression of polarity boundaries in CPCP PFNP13-1A and Newark-Hartford APTS. U-Pb zircon date for Manicouagan crater impact melt rocks (Ramizani et al., 2005), which are characterized by normal polarity (Larochelle and Currie, 1967), is shown for reference. Inset shows a paleocontinental reconstruction of Pangea (from Kent et al., 2018) positioned according to a 220 Ma mean composite paleopole (Kent et al., 2014) with some key continental localities indicated by filled circles connected by arrows to their relative positions at 200 Ma by open circles.

yet been positively identified in the core either. There is also no reason to suspect these markers are related to the cause of the Adamanian–Revueltian boundary or the Manicouagan impact. Hence, additional fieldwork is needed to recover an unambiguous polarity stratigraphy to register the biotic transition with the core magnetic stratigraphy. We do know that at least broadly speaking the marine turnover is close in time to the Adamanian–Revueltian boundary. However, additional work will be needed, presumably by others, to place the marine biotic changes in a magnetostratigraphic context that is thus far lacking except for a very few sections (e.g., Muttoni et al., 2004, 2014).

3. Is the apparent pattern of latitudinal biotic provinciality seen in the Late Triassic supported by high-resolution, independent (i.e., non-biostratigraphic) correlations and does that change with climate-related environmental proxies? The match of the magnetic polarity stratigraphy and zircon U-Pb dates from core 1A to the Newark-Hartford APTS (Kent et al., 2018) and a rather obvious correlation with magnetic polarity stratigraphy records through North and South America shows that the apparent pattern of latitudinal biotic provinciality seen in the Late Triassic is supported by high-resolution independent (i.e., non-biostratigraphic) correlations (Fig. 16). This means that the strong biotic provinciality of Triassic Pangea, and the 30 million-year delay in the rise of dinosaurian ecological dominance in the tropics (White-

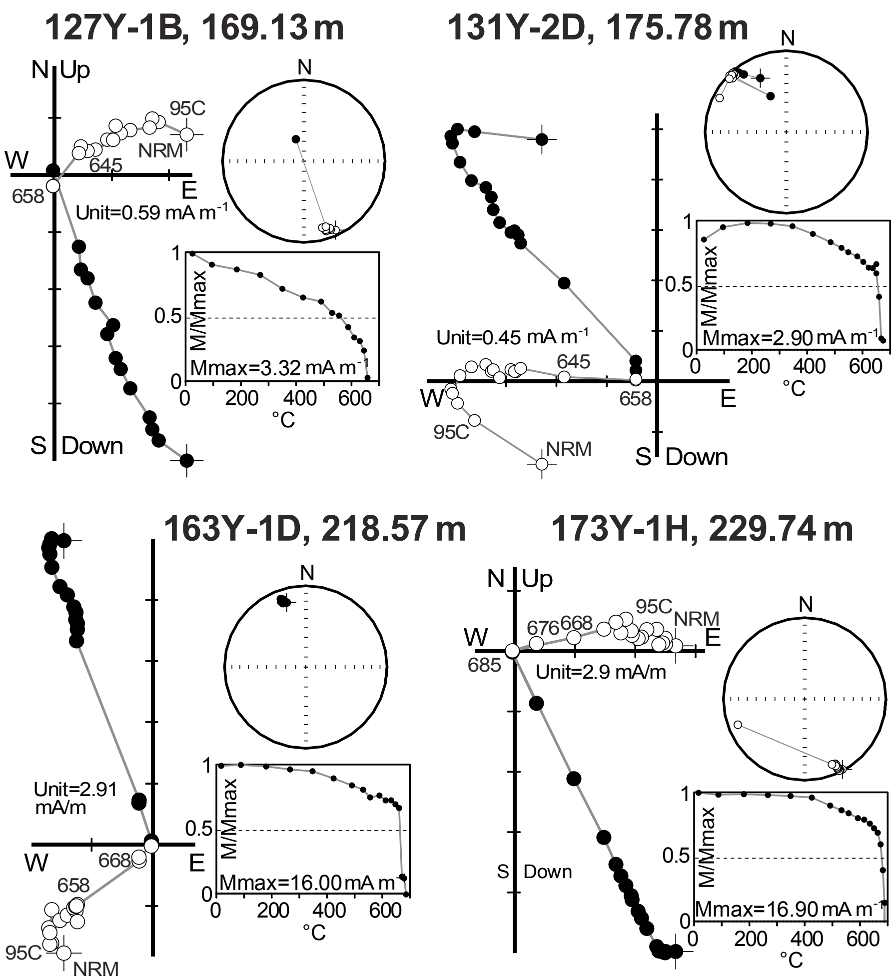

Figure 14. Examples of orthogonal progressive demagnetization diagrams for the Moenkopi Formation showing the end point of the magnetization vector plotted onto the horizontal (filled symbols) and vertical (open symbols) planes (NS-EW, EW-Up/Dn) for individual specimens from core segments of Moenkopi Formation rocks intersected in CPCP Phase 1 Core 2B that have been subjected to progressive thermal demagnetization. Demagnetization steps, in temperatures (°C) are given alongside selected vertical projection data points. NRM is the natural remanent magnetization. Also shown are normalized intensity decay plots showing response to progressive thermal treatment (abscissa is temperature, °C) and equal area stereographic projections of the magnetization vector measured at each step. Note that the coordinate axes for each and every diagram are identical in orientation and the diagrams are in geographic coordinates, assuming that each core segment is properly oriented.

side et al., 2011, 2015) indicated by previous correlations using the Newark-Hartford APTS, is not an artefact of biostratigraphic miscorrelation as asserted by some (e.g., Lucas, 2018), but a real feature of that world which can now be quantified both in time and space (Kent et al., 2018).

4. Is the orbitally paced (Milankovitch) cyclical climate change recorded in the Newark basin lacustrine deposits reflected in the largely fluvial Chinle and Moenkopi formations? Based on work still underway, a perhaps surprising preliminary result from the Petrified Forest and upper Sonsela members is that the 405 kyr cycle is in fact reflected in the Chinle Formation, as seen in the redox-sensitive magnetic susceptibility logs (Olsen et al., 2017) (Fig. 5). A lower-frequency cycle around 1.8 Myr is present as well and is also seen in the Newark record (Olsen et al., 1999). Higher-frequency orbital cycles have yet to be identified with certainty, although there is a hint of some ∼ 100 ky cyclicity in the magnetic susceptibility logs. Additional work with other environmental proxies, including the CT scans of paleosol fabrics (Fig. 8), and analysis of the rest of the section and cores should provide a deeper knowledge of how the cycles are expressed in the fluvial environments.

5. Do $p\mathrm{CO_2}$ proxies in the western US track those from the eastern US, and how do they relate to the records

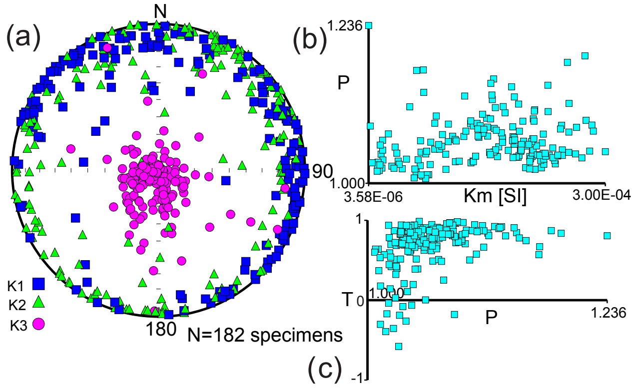

Figure 15. Preliminary anisotropy of magnetic susceptibility (AMS) data from Moenkopi Formation rocks intersected in CPCP Phase 1 Core 2B. **(a)** The stereographic projection shows the principal susceptibility axes ($K_1, K_2, K_3 = K_{\mathrm{max}}, K_{\mathrm{int}}, K_{\mathrm{min}}$) for each specimen measured (lower hemisphere projections). **(b)** The anisotropy parameter P, where $P = K_{\mathrm{max}}/K_{\mathrm{min}}$, is plotted vs. bulk susceptibility for each specimen measured. **(c)** The anisotropy parameter T, where T, the shape parameter ($= ([2\ln K_{\mathrm{int}} - \ln K_{\mathrm{max}} - \ln K_{\mathrm{min}}]/[\ln K_{\mathrm{max}} - \ln K_{\mathrm{min}}]$) is plotted vs. P. T values close to 1.0 are associated with strong oblate fabrics. In **(a)** the data from most Moenkopi rocks show a fabric that is typical of very fine-grained detrital sedimentary rocks, with the minimum susceptibility axis essentially vertical and overall well grouped. The principal susceptibility axes are plotted assuming that all sampled core segments are properly oriented; as discussed in the text this assumption is likely not always valid and thus improper core orientation may be a source of some of the observed dispersion in the data. An additional source of dispersion is that some Moenkopi facies may have preserved a well-defined sedimentary imbrication fabric, where the minimum susceptibility axis is canted from the vertical.

of environmental change seen in the cores, and other areas? Preliminary results from parts of core 1A show that the carbonate paleosol $p\mathrm{CO_2}$ proxy does yield comprehensible results consistent with those from the eastern US (Schaller et al., 2015; Whiteside et al., 2015). At least one major fluctuation falls in the age range of the CPCP-PFNP13-1A core with a $p\mathrm{CO}^2$ local minimum at about 211–212 Ma (Knobbe and Schaller, 2018), associated with a Norian temperature low (Trotter et al., 2016). There are also encouraging results that atmospheric $\mathrm{O_2}$ concentrations are obtainable from the same soil carbonates from the CPCP cores and eastern North America (Schaller et al., 2017). Other fluctuations in $p\mathrm{CO_2}$, such as the Rhaetian drop and the Hettangian rise associated with the emplacement of the Central Atlantic Magmatic Province (CAMP) as well as the supposed Carnian "Pluvial" (Ruffell et al., 2016), do not fall within the age range of these cores.

6 Outreach and broader impacts

Petrified Forest National Park is a major tourist destination with some 600 000 visitors per year from around the world who are predisposed to be receptive to a geologic narrative. To highlight the CPCP and its potential for public education and outreach, the National Park Service posted a link devoted to the project (https://www.nps.gov/pefo/learn/nature/coring.htm, last access: September 2018), and produced a flyer that was distributed while we were on-site. During drilling we hosted several tours for local residents and tourists. There was significant international to local publicity associated with the project, including Nature (http://www.nature.com/news/geologists-take-drill-to-triassic-park-1.13866, last access: September 2018), PLos Blogs (http://blogs.plos.org/paleo/2013/11/21/the-colorado-plateau-coring-project-getting-dates-in-the-triassic/, last access: September 2018), Arizona Geology (http://arizonageology.blogspot.com/2013/11/scientific-core-drilling-at-petrified.html, last access: September 2018), Discover Magazine (http://discovermagazine.com/2015/may/18-sands-of-time, last access: September 2018), National Geographic (http://phenomena.nationalgeographic.com/2013/11/19/getting-to-the-core-of-the-triassic/, last access: September 2018), WNYC (https://www.wnyc.org/story/shutdown-stymies-scientific-research/, last access: September 2018), and the Arizona Daily Sun (http://azdailysun.com/news/local/petrified-forest-a-fossil-every-inches/article_ee70579c-4906-11e3-9324-001a4bcf887a.html, last access: September 2018). A time-lapse video by Max Schnurrenberger of rig set up and coring set to music is posted as well (https://www.youtube.com/watch?v=0cbWuKnmVKk and linked to the CPCP site http://www.ldeo.columbia.edu/$\sim$polsen/cpcp/PFCP_13_main.html, last access: September 2018) and the LacCore group developed and maintains a Facebook page for the project (https://www.facebook.com/Colorado-Plateau-Coring-Project-1436554049899932/, last access: September 2018), with news updates throughout drilling, and coordinated workforce development training in drilling and core workflows for five people, which developed over 300 likes and nearly as many followers during the coring period. The ultimate goal of Petrified Forest National Park is to provide a million-year (at least) resolution time line of the 20 million-year history of the area during the Triassic and then tying this through to the modern era. The data from the cores will be a big part of generating this story as exhibits develop. A permanent website for the project was developed and is maintained by PEO (http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html, last access: September 2018). The latter has seen over 12 000 visitors.

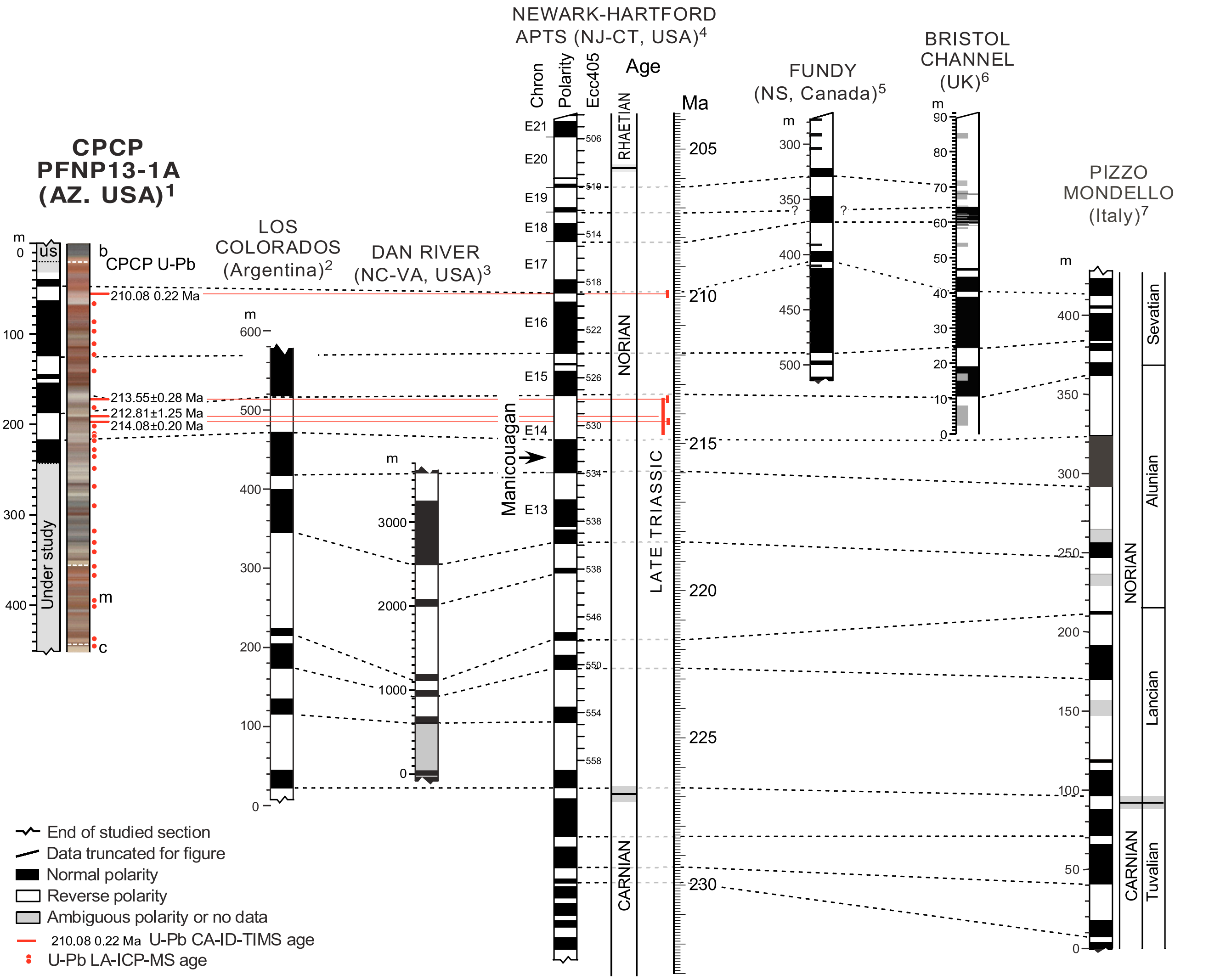

Figure 16. Paleomagnetic polarity stratigraphy of the upper part of the Chinle Formation in CPCP PFNP-13-1A correlated with the Newark-Hartford APTS and sections in Argentina, eastern North America (Dan River and Fundy basins), the UK, and Italy. Dotted white lines in the CPCP section are formation boundaries. Note that no correlation is implied for the Chinle Formation below 245 m stratigraphic depth. Sections are shown in stratigraphic (thickness) coordinates, except the APTS, which is in time, pinned to zircon U-Pb dates from the Central Atlantic Magmatic Province (CAMP) (Blackburn et al., 2013) and tuned to the 405 kyr orbital cycle. CPCP zircon U-Pb ages are correlated (horizontal red lines) with the Newark-Hartford APTS by paleomagnetic polarity stratigraphy and a linear age–depth model (Kent et al., 2018) (with the analytical error shown by the vertical red bars). Each paleomagnetic polarity stratigraphy is independently correlated in this diagram with the Newark-Hartford APTS via the first and last polarity boundaries according to the original author (not shown for the sections truncated here). Additional abbreviations are Ecc405, the Jupiter–Venus eccentricity cycle of a 405 kyr period; us, unsampled; b, Neogene Bidahochi Formation; m, Early to nominally Middle Triassic Moenkopi Formation; and c, Early Permian Coconino Sandstone. Sources are [1] Kent et al. (2018); [2] Kent et al. (2014); [3] Kent and Olsen (1999) and Olsen et al. (2015); [4] Kent et al. (2017); [5] Kent and Olsen (2000); [6] Hounslow et al. (2004) and Briden and Daniels (1999); and [7] Muttoni et al. (2004) and Kent et al. (2017).

The CPCP has included and will continue to include significant career training and mentoring. Thus far, this has included post-doctoral fellow Charlotte Miller (University of Oslo); PhD graduate fellows Cornelia Rasmussen (University of Utah), Sean Kinney (Columbia University), and Viktória Baranyi (University of Oslo); MSc graduate students Dominique Geisler (University of Arizona) and Hesham Buhedma (University of Texas at Dallas); and undergraduate honors student Julia McIntosh (University of Texas at Dallas).

7 Continuing science and plans

The Petrified Forest National Park part of the CPCP is in the post-drilling science phase. Preliminary results were presented at the AGU national meetings in 2013, 2014, 2016 (P. E. Olsen et al., 2013, 2014; Geissman et al., 2014; Buhedma et al., 2016), the Geological Society of America national meeting (Irmis et al., 2014), the Society of Vertebrate Paleontology Meeting in Berlin (P. Olsen et al., 2014a), the International Paleontological Congress in Mendoza Argentina (P. Olsen et al., 2014b), the International Geological Congress in Cape Town, SA (P. Olsen et al., 2016; P. E. Olsen et al., 2016; Geissman et al., 2016), and an AGU national meeting special session in 2017 entitled, "Chronostratigraphic Advances Integrating Paleomagnetism, Tephra, Climate Correlation, and Other Stratigraphic and Proxy Methods to Solve Earth System Processes and Events" (Irmis et al., 2017; Kent et al., 2017b; McIntosh et al., 2017; Olsen et al., 2017; Rasmussen et al., 2017; Schaller et al., 2017). Peer-reviewed publications have begun appearing this year (e.g., Kent et al., 2018). It is not an overstatement to conclude that the results from the CPCP project have transformed one of the poorest calibrated intervals of the Phanerozoic to one of the best. Our success at providing an independent and globally exportable zircon U-Pb-calibrated, paleomagnetic polarity stratigraphy, and atmospheric gas constraints from these kinds of continental sequences and their applicability to regional and global problems, has already resulted in a fundamental advance (Kent et al., 2018) and will spur future efforts in other parts of the geologic column. Plans for CPCP Phase 2 are underway with an international workshop that will coordinate efforts at building on Phase I of the CPCP, extending the core record though the rest of the Late Triassic, the Triassic–Jurassic transition, and nearly the complete Early Jurassic. The CPCP Phase 2 project will be coordinated with the ongoing JET project (https://www.facebook.com/JETMochras/, last access: September 2018) in the cyclical Early Jurassic marine epicontinental Jurassic of the UK. Ideally it will be paired with coring a high-latitude site, together resulting in an unprecedented synoptic view of Triassic to Jurassic $p\mathrm{CO}_2$, climate evolution and orbital pacing, and biotic transitions, including two mass extinctions and the rise to ecological dominance of the dinosaurs. A ICDP-funded workshop on these possible coring projects is planned for May 2019.

Team list. G. Bachman, V. Baranyi, R. Blakey, K. Brady Shannon, H. Buhedma, M. Colbert, D. Edey, G. Gehrels, J. Geissman, D. Giesler, Z. Haque, R. Irmis, D. Kent, S. Kinney, W. Kürschner, C. Lepre, J. MacIntosh, J. Maisano, C. Miller, R. Molina-Garza, R. Mundil, A. Noren, R. O'Grady, P. Olsen, W. Parker, C. Rasmussen, M. Schaller, D. Schnurrenberger, J. Sha, J. Whiteside, N. Zakharova. The CPCP teams include all of the authors plus R. Blakey, Z. Haque, and J. MacIntosh.

Data availability. The underlying data for this paper, not already presented in previous papers, are freely available from https://osf.io/5vd8u/ at this persistent DOI: https://doi.org/10.17605/OSF.IO/5VD8U (Stone et al., 2016). The archive split of the CPCP cores are stored at the LacCore, National Lacustrine Core Repository (http://lrc.geo.umn.edu/laccore/repository.html, last access: September 2018) and the working split is at the Rutgers University Core Repository where available (https://eps.rutgers.edu/centers-institutes/rutgers-core-repository, last access: September 2018).

Author contributions. PEO, JWG, DVK, GEG, RM, RBI, WGP, WMK, RMG, GHB, RMG, JHW, GHB, RCB, and JS designed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, WGP, NZ, WMK, CM, VB, HB, MFS, JHW, DS, AN, KBS, RO'G, MWC, JM, DE, STK, RMG, GHB, RCB, and JS designed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, WGP, NZ, WMK, CM, VB, HB, MFS, DS, AN, KBS, RO'G, MWC, JM, DE, STK, RMG, JMI, ZH, performed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, NZ, WMK, CM, VB, HB, MFS, JHW, and STK analyzed data. PEO, JWG, DVK, GEG, RM, RBI, WGP, WMK, CM, JHW, and STK wrote the paper.

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

Disclaimer. Any opinions, findings, or conclusions of this study represent the views of the authors and not those of the U.S. Federal Government.

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Scientific Drilling
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Progress Reports

A high-resolution climate record spanning the past 17 000 years recovered from Lake Ohau, South Island, New Zealand

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Abstract. A new annually resolved sedimentary record of Southern Hemisphere mid-latitude hydroclimate was recovered from Lake Ohau, South Island, New Zealand, in March 2016. The Lake Ohau Climate History (LOCH) project acquired cores from two sites (LOCH-1 and -2) that preserve sequences of laminated mud that accumulated since the lake formed ∼ 17 000 years ago. Cores were recovered using a purpose-built barge and drilling system designed to recover soft sediment from thick sedimentary sequences in lake systems up to 150 m deep. This system can be transported in two to three 40 ft long shipping containers and is suitable for use in a range of geographic locations. A comprehensive suite of data has been collected from the sedimentary sequence using state-of-the-art analytical equipment and techniques. These new observations of past environmental variability augment the historical instrumental record and are currently being integrated with regional climate and hydrological modelling studies to explore causes of variability in extreme/flood events over the past several millennia.

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1 Introduction

The Lake Ohau Climate History (LOCH) project is an international initiative involving scientists, engineers, drilling professionals, and students from New Zealand, Italy, Republic of Korea, United States of America, and Australia. Between 12 February and 5 March 2016 our drilling operations team completed a field expedition that recovered core from an 80 m thick sedimentary sequence of laminated mud that lies beneath the floor of Lake Ohau, South Island, New Zealand (Fig. 1). This sequence accumulated after glacial ice retreated from the lake basin approximately 17 900 years ago (Putnam et al., 2013). Four holes at two sites (LOCH-1 and LOCH-2, Fig. 1) were drilled during this operation and a total of 229 m of sediment was recovered. This new sedimentary record offers a high-resolution (annual to decadal) climate record for the Southern Hemisphere. This progress report provides an overview of the scientific objectives of the LOCH project, summarizes drilling operations, highlights the new lake drilling capability that was developed and utilized for the project, and provides an update on the status of scientific work.

1.1 Scientific rationale

Inter-annual climate variability around New Zealand and the south-western Pacific is primarily driven by the position and intensity of Southern Hemisphere westerly winds (SWW) which are sensitive to changes in the Southern Annular Mode (SAM) (Ummenhofer and England, 2007; Ummenhofer et al., 2009; Wang and Cai, 2013), the influence of El Niño–Southern Oscillation (ENSO) (Ummenhofer and England, 2007; Wang and Cai, 2013) and the Interdecadal Pacific Oscillation (IPO) (Folland et al., 2002; Salinger et al., 2001). These climate phenomena have a considerable influence on New Zealand rainfall, which is clearly illustrated by a reduction in South Island summer precipitation of up to 40 % over the past 30 years in response to a trend towards a high positive phase of SAM (Ummenhofer et al., 2009). Concomitant southward migration and strengthening of the SWW have been driven by increasing atmospheric CO_2 concentrations (Shindell and Schmidt, 2004) and ozone depletion (Thompson and Solomon, 2002). Leading hypotheses and modelling results suggest that the SWW will continue to shift south and intensify as climate warms (Toggweiler and Russell, 2008; Chang et al., 2012; Barnes and Polvani, 2013), with a significant impact on precipitation at the mid-latitudes of the Southern Hemisphere (Garreaud, 2007; Lim et al., 2016). However, our ability to interrogate these hypotheses and climate simulations with empirical data is limited by the relatively short duration of instrumental records. High-fidelity climate archives that span millennia, including intervals of past warmth, are required to place current anthropogenic climate change into a longer-term perspective and allow a more robust assessment of climate dynamics at the southern mid-latitudes.

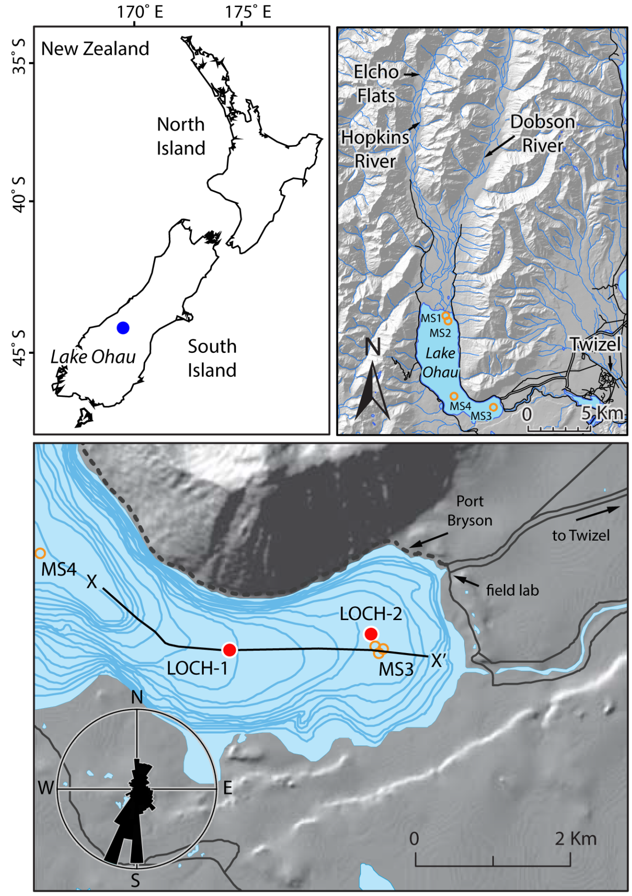

Figure 1. Location of Lake Ohau, South Island, New Zealand. Orange circles: monitoring sites 1–4; red dots: LOCH drill sites; line X–X′: location of the seismic line illustrated in Fig. 3. Gravel access road indicated by the dashed line in the bottom panel. The rose diagram shows that the dominant wind direction is from the north-north-east.

The Lake Ohau basin (44°10′ S, 169°49′ E) contains a thick sedimentary sequence that accumulated following glacial retreat that began 17 900 years before present (BP) (Schaefer et al., 2006; Barrell et al., 2011; Putnam et al., 2013). The study area is located at the northern boundary of the westerly wind belt and offers a unique location to examine the hydrologic response to changes in the SWW. Moorings fitted with instruments to measure currents, turbidity, and water temperature have been deployed in the lake since 2012. Data obtained from these instruments have been integrated with local weather station data, outflow measurements, and sediment trap data. Results show that sediment transport and deposition in the lake reflect seasonal variations in regional hydroclimate (Roop et al., 2015a, b). The 6 m long cores that were recovered from beneath the lake

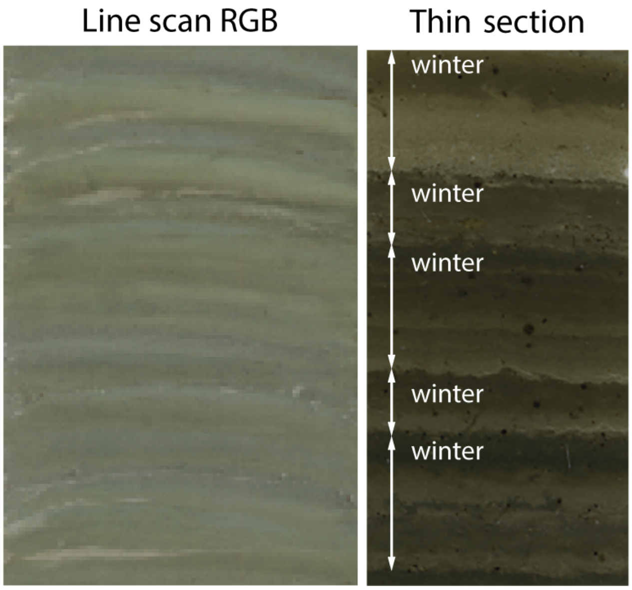

Figure 2. Line scan image from a 6 m long Mackereth core recovered from the sedimentary section near site MS-3. A petrographic thin section from the same core highlights sedimentary couplets that include lighter (summer) and dark (winter) layers.

bed near LOCH-2 (Fig. 1) using a Mackereth coring system (Mackereth, 1958) revealed a sedimentary sequence comprising mm-scale couplets of light and dark layers (Fig. 2). A detailed chronology for this sequence has been established by combining well-defined ^{137}Cs and ^{210}Pb profiles, layer counts, and ^{14}C dates (Roop et al., 2015a; Vandergoes et al., 2018). The age model allows us to correlate the sedimentary sequence with hydroclimate data and shows that sedimentary couplets exhibit strong correspondence with lake inflow and outflow. Specifically, deposition of thin dense layers that are composed of the finest particle fraction occurs during winter. Less dense coarser layers are deposited during spring and summer and are generally thicker than the winter layers (Roop et al., 2015a). Measured annual outflow from Lake Ohau correlates with annual precipitation measured over most of the South Island (Ummenhofer and England, 2007). These data suggest that the package of sediment preserved beneath Lake Ohau offers an unprecedented opportunity to reconstruct South Island hydrology at annual timescales over the Holocene and at high resolution since the LGM. This record is of major global significance as similar high-resolution paleoclimate data series are exceptionally rare at the Southern Hemisphere mid-latitudes.

1.2 Regional setting

Lake Ohau occupies an intermontane basin that formed as ice advanced across the Mackenzie Basin during Late Quaternary glaciations (Golledge et al., 2012; Putnam et al., 2011, 2013). Terminal glacial moraines were deposited at the southernmost end of the basin 17 900 years ago and form a natural dam (see Fig. 11 in Putnam et al., 2013). Today, the lake is fed by the Dobson and Hopkins rivers, which flow from the continental divide, draining a combined area of 924 km^2, and converging just upstream of the lake delta. These two rivers contribute ∼ 85 % of the total annual inflow (Woods et al., 2006). The lake has a mean depth of 74 m and reaches 129 m at its deepest point (Irwin, 1978). Water levels typically fluctuate by $<$ 0.3 m throughout the year and are controlled via hydroelectric power infrastructure that was built in the 1970s and comprises a control gate and weir that cut the terminal moraine. Prior to construction, lake levels varied naturally by ∼ 0.5 m, as determined by near-daily measurements dating to 1926.

Lake Ohau sits at the northern edge of the westerly wind system that dominates zonal air flow at the southern mid-latitudes. The north–south alignment of the Hopkins and Dobson valleys means the predominant wind flow over the lake is from the north, with a secondary south easterly mode. The highest wind speeds (up to 160 km h^{-1}) come from the north and occur most frequently in spring and early summer when the westerly wind belt is located at its northernmost extent. During this period gusts over 100 km h^{-1} are common. There is a marked diurnal wind cycle in summer, with the calmest conditions in the morning and windiest in the late afternoon. Air temperature around the lake margin ranges between a winter mean of 6.2 °C, although it frequently drops below freezing at night, and summer mean of 14.3 °C and decrease at a rate of ∼ 0.5 °C/100 m increase in elevation. Mean rainfall increases from ∼ 640 mm year^{-1} at Twizel (elevation 470 m) to over 2800 mm year^{-1} at Elcho flats (elevation 739 m) in the Hopkins Valley (Fig. 1).

1.3 Lake hydrodynamics

We initiated a hydrologic monitoring programme in 2009 that was expanded in 2012 to examine the physical processes that influence lake sedimentation and to help identify an optimal location to recover a long climate record. Moorings with temperature loggers and turbidity meters were deployed at monitoring sites (MS) −1 and −2 near the large delta at the northern end of the lake and MS-3 at the distal end of the lake (Fig. 1). Water current velocity data were collected at the delta between January 2012 and January 2013 using a RDI 1200 kHz, four-beam acoustic Doppler current profiler (ADCP) moored on the lake bottom at a depth of 25 m (Fig. 1, MS-1) and a RDI 600 kHz, four-beam ADCP at depth of 50 m (Fig. 1, MS-2). These instruments captured a series of major summer inflow events that occurred between 31 December 2012 and 15 January 2013, during which period one of the instruments was lost (Cossu et al., 2016). A Sontek 250 kHz ADCP was deployed in September 2013 in the central basin in 129 m of water (Fig. 1, MS-4). This instrument samples water velocity and signal amplitude (∼ particle concentration) over the entire water column in 2 m depth incre-

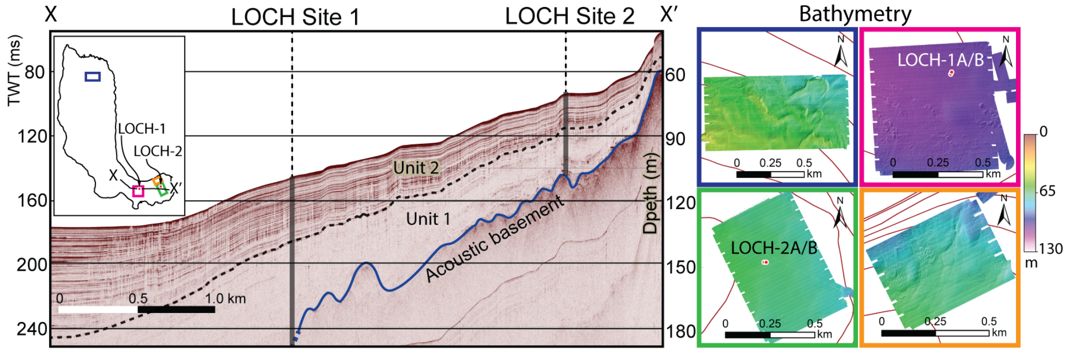

Figure 3. Seismic (boomer) reflection profile and sonar data from Lake Ohau showing the progressive thickening of the post-glacial sequence toward the central lake basin. The inset map shows the location of profile X–X′, LOCH drill sites (red dots), and bathymetric surveys (coloured squares correspond to data shown at the right of the figure).

ments. Several types of sediment trap have been deployed over the monitoring period, including simple centrifuge tubes attached at discrete intervals along mooring lines at MS-1, -2, and -3 (Fig. 1), a 46 cm diameter single cone trap (first deployed in May 2009), and a NiGK Corporation SMD-13S-6000 carousel trap system with a 36 cm diameter cone and set up with fortnightly rotations of sample bottles (first deployed in August 2014). Both large sediment traps are located at MS-3 near the distal end of the lake in 68 m of water (Fig. 1).

Results of this monitoring programme indicate that Lake Ohau is isothermal in winter when water column temperature decreases to $\sim 8\,°C$. The lake becomes thermally stratified in November and surface temperatures reach maximum values of $\sim 18\,°C$ between January and March. Large inflow events ($Q \geq 500\,m^3\,s^{-1}$) that follow strong summer rainstorms trigger high-concentration turbidity currents, which are the main agents for sediment delivery and deposition. During winter, smaller turbidity currents also occur after rain events but typically flow along the lake bottom as the temperature of the inflowing river water is below that of the lake. A conceptual hydrologic sedimentation model was developed from regional climatic and monitoring data (Cossu et al., 2016). In this model, hydrodynamic processes, which are primarily controlled by changes in lake temperature, produce the seasonal signal that is preserved in sediments at the distal end of the lake. Inflow events between late spring and early autumn generally transport sediment in interflows and disperse clastic particles across the entire lake basin. In contrast, cold, dense winter inflow events generally plunge and flow across the basin near the floor of the lake. These bottom flows cannot carry sand-sized sediment into shallower regions at the distal end of the lake. Fine grained silt and clay that remain suspended from spring to autumn inflow events settle out at the distal end of the lake during winter. This seasonal contrast produces a distinct winter layer of very fine silt (Fig. 2). In contrast, sediment layers at the delta and central basin record a complex event stratigraphy, including dm thick sandy turbidites.

2 Drill site selection and characterization

2.1 Acoustic surveys

Sub-bottom profile (3.5 kHz "Chirp") and high-resolution seismic reflection (boomer) data were collected during several surveys between 2011 and 2015. The seismic sequence (Fig. 3) is characterized by an acoustically opaque unit with an undulating surface (acoustic basement) that is overlain by a unit with indistinct parallel reflections (Seismic Unit 1) and a unit with strong parallel reflections (Seismic Unit 2). Reflections in Seismic Unit 2 can be traced across the basin and acoustic layers thicken toward the centre of the basin where the total post-glacial sequence is at least 150 m thick. We inferred that the basal unit (acoustic basement) was composed of diamicton deposited as glacial moraine and sub-glacial till that accumulated as ice last retreated from the lake basin. In contrast, the layered sequences (Seismic Units 1 and 2) accumulated once the lake had formed. Seismic Unit 1 was initially interpreted as a sequence of proglacial sediments and homogeneous muds that accumulated during glacial retreat. Seismic Unit 2 was interpreted as a Holocene sequence of well-stratified, laminated sedimentary couplets which represented a continuation of the stratigraphy observed in short cores recovered from the upper 6 m of sediment fill. A high-frequency bathymetric sonar and side scan survey was conducted over targeted regions across the delta system and at the distal end of the lake using a Geoswath Plus 500 kHz phase-measuring bathymetric sonar mounted on a Teledyne Gavia autonomous underwater vehicle. Measurements collected from this untethered vehicle produce bathymetry with better than 20 cm spatial resolution that reveals the subaqueous geomorphology of the lake floor in exceptional detail. In total eight $\sim 1 \times 1$ km grids were surveyed around the lake from the inflow at the northern end to the outflow weir at the southern end (Fig. 3). These data demonstrated a wide range of geomorphic features within the lake, including evidence of sidewall slumping, delta foreset morphology, and long runout sediment flows from sidewall mass movement. These data were also used to examine lake floor morphology at the chosen drill sites and evaluate their suitability as drilling targets.

2.2 Sediment distribution

Whereas the central basin offers the greatest potential to recover the thickest/highest temporal resolution paleoclimate record, analysis of short cores from the deepest regions of the lake reveal a complex sequence of layers that include three primary sedimentary lithofacies: (1) 5–10 mm thick dark grey very fine sandy silt and light grey medium silt couplets; (2) 10–100 mm thick beds of dark grey fine sand that normally grade into grey medium silt; and (3) up to 1 m thick graded beds characterized by a medium to fine sand base, very fine sandy silt unit, and fine silt cap. The two thinner units likely formed during inflow events of different magnitudes, whereas the thick units formed during flows generated by mass-wasting on the basin margins, possibly following seismic events. This complex event stratigraphy precludes our ability to identify a clear annual signal – a key requirement for paleoclimate research objectives. In contrast, distinct summer–winter layers accumulate at the distal end of the lake and make the region the best target to resolve an annual stratigraphy (Roop et al., 2015a). These annual layers form in response to changes in sediment input and hydrodynamics through the year. Sediment trap data from MS-3 indicate that accumulation at the distal end of the lake generally ranges between 0.7 and 4.0 $\mathrm{mg\,cm^{-2}\,day^{-1}}$ between November and May but drops below 0.5 $\mathrm{mg\,cm^{-2}\,day^{-1}}$ between June and October. This seasonal variability in sediment dispersal and accumulation rate produces sedimentary couplets that reflect an annual cycle and make the distal end of the lake a primary target for an annually resolvable paleoclimate record.

2.3 Environmental factors

Environmental conditions also factored into site selection. Wind speeds up to 160 $\mathrm{km\,h^{-1}}$ have been recorded at the head of the lake and air flow can be consistently strong in spring and early summer. The prevailing northerly and northwesterly winds funnel down the 10 km length of the lake and can produce short-period ($\sim$ 4 s) waves at least 2 m high. Drilling in these conditions is not possible. The south-eastern end of the lake is generally sheltered from these prevailing winds and wave heights are less than in the central basin, which meant that the south-eastern location was likely to provide calmer conditions for drilling.

3 Drill system design

Operating requirements for the LOCH project were unlike any encountered during previous scientific drilling activities in New Zealand. The project needed a drill system that could operate in deep water (at least 100 m) and recover near-continuous high-quality core through a sequence of soft sediment (sand and mud) $\sim$ 80 m thick. Furthermore, wind and wave conditions at Lake Ohau can be extreme, so the ability to quickly mobilize the drilling system and move it to shelter in the event of high winds and rough water conditions, and relocate the rig above the site and re-enter the hole once conditions improved, was a key operation capability design requirement.

A fit-for-purpose drilling system was built in 2015 to meet LOCH project requirements, but the potential for deployment in a range of hard to access locations around the world has been considered in the design and build. Major components include a state-of-the-art barge; a riser system; soft sediment coring tools; and a drill rig. The initial barge concept was developed by Marine Surveyors (Mtech Ltd) and Webster Drilling and Exploration Ltd in collaboration with engineers at Victoria University of Wellington. The barge comprises two 11.8 m long pontoons that are constructed of a 6 mm steel plate and are connected by threaded Ishibek bars that run through steel transverse frames. It has an unloaded weight of 13 t and can be disassembled for transport and fit into one standard 40 ft long shipping container. A Webster Drilling HPP 600 rig was chosen for the LOCH operation. This rig is a through the head drive diamond coring rig capable of 13 t pull-back, although the barge system in its current drilling operational configuration can only support a pull-back of 8 t. The operational load included the rig and power pack (4000 kg), 108 m of PWT casing (2315 kg), 200 m of HWT drill string (3498 kg), and 600 L of fuel (600 kg), which provided the capability to complete the LOCH objectives. The system can support a larger load if a self-supporting riser is used, which would allow deployment of up to 400 m of PQ string and bring targets up to 400 m beneath the barge floor within reach.

A self-supporting riser was included in drill system design specifications to allow circulation of drilling mud to enhance core recovery and quality. A riser would also allow deployment of HWT drill string in "deep" water drilling environments and hole re-entry capability if required. An airbag system was designed to tension the riser and keep it separated from the barge so that, in the event of inclement weather, the platform and rig could be removed from the drill site, towed to sheltered anchorage, and subsequently repositioned over the riser once weather improved. If a disconnect was required, HWT drill string would be clamped above the slips and hung off the top of the PWT casing. Additional weight of the drill rod to the lake floor would be compensated for by increasing the buoyancy in the air bag. The four mooring lines would be tied off on the self-buoyant riser and the barge could then be towed off site.

4 Field operations

Drilling in winter, which is the calmest period, was considered impractical due to the short number of daylight hours (~ 8.5 per day in July vs. ~ 13.5 in February) and temperatures that frequently drop below 0 °C. Environmental conditions in February–March are generally more settled than earlier in the summer. Wind speeds rarely exceed 60 km h^{-1} and typically range between 0 and 15 km h^{-1}, and average day–night temperatures range from 8.5 to 24 °C. This period was selected for drilling to mitigate risks associated with adverse weather.

Primary access to the lake was via a gravel road that traverses the eastern margin of the lake (Fig. 1). A concrete boat ramp and jetty located at Port Bryson at the southeastern end of the lake are accessible from the road. The barge and drill system were delivered to the lake edge on two articulated trucks and lifted into position with a 30 t crane. Barge assembly and rig fit-out was completed in ~ 1/2 day. An 11.09 m Seacraft alloy research vessel, the *Beryl Brewin*, was also delivered to Port Bryson on a tractor trailer unit and lifted into the lake with the crane. This vessel was used to manoeuvre the barge, deploy anchors, and serve as a support tender and core processing platform during drilling operations (Fig. 4). The barge was four-point-anchored to the lake bed using standard plough anchors and chain attached to 400 m of low stretch 12 mm Dyneema® 12 strand braided rope. Anchor lines were tensioned off four hydraulic winches on the deck of the barge and powered off the rig's hydraulic power unit (Fig. 4). This system allows the rig to be repositioned to drill multiple offset holes without having to reset the anchors.

PWT casing (139.7 mm (5.5″) external diameter/127.0 mm (5.0″) internal diameter) was used as a riser and was deployed with the main rig winch. The riser was clamped with a bullring and slips installed below the barge deck and in front of the drill mast. A 1.3 m^3 concrete block weighing 1.3 t (in air) was connected to the bottom of the riser and used as a lake floor anchor. A 2 m long length of PWT casing with a flange at its top end was embedded in the concrete block to provide a "stinger" that extended 1 m into the sediment below the base of the block. Ports in the flange allowed wash-in cuttings to vent on top of the anchor block.

An airbag system comprising a 5 t wrap around air bag was shackled to 203 mm (8″) internal diameter flanged pipe (Fig. 4) and was connected to the riser so that the top of the air bag sat ~ 2.8 m below the lake water surface. Mooring lines were connected to four points at the bottom of the airbag pipe with blocks (and pulleys). However, once deployed, the drilling crew recognized that the top of the airbag system was mounted too close to the water surface and

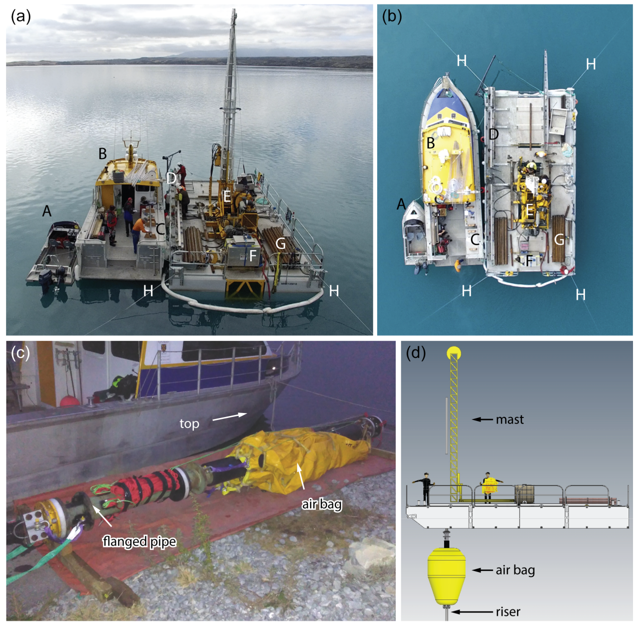

Figure 4. (a, b) – Photographs of the drill system deployed at Lake Ohau shown from stern view (note LGM terminal moraine in distance) and from above. A – alloy support vessel used to transport core to shore; B – RV *Beryl Brewin*; C – core curation area; D – coring tool work area; E – Webster Drilling HPP 600 rig; F – double lined 350 L rig fuel tank; G – drill pipe; H – anchor lines. **(c, d)** – air bag attached to flanged pipe in pre-deployment configuration lying beside tender vessel; schematic diagram of barge and air bag in deployed configuration.

that the airbag volume/buoyancy was fluctuating in response to pressure changes caused by low-amplitude lake surface waves. The airbag system's automated pressure control was unable to maintain constant buoyancy during these short-period pressure changes, so the system was disconnected. Future deployments could include a riser buoyancy system that utilizes a light rigid shell cylindrical tank, instead of an inflatable air bag, which should mitigate buoyancy issues encountered during LOCH project operations. Drill crew members would control the volume of water or air in the tank to manage buoyancy and maintain a small positive air pressure in the tank to ensure it did not collapse. This system should be unaffected by variable pressure created by wave motion and the barge-riser disconnect capability could then be utilized if required.

A QD Tech, Inc wireline retrievable hydraulic piston corer (HPC) that recovers a 66.3 mm diameter core inside a plastic (Ocean Drilling Program; ODP) core liner was latched into the core barrel deployed in an HWT drill string (114.3 mm (4.5″) external diameter/101.6 mm (4″) internal diameter) within the PWT casing. Lake water was pumped into the drill string until a pressure of 4.14 MPa (600 psi) was reached and shear pins holding the corer in place failed, allowing it to "fire" into the sediment. The sample tube could extend a

Table 1. Drill site location data and core information.

Site	Latitude	Longitude	Water depth (m)	Number of core runs	Max. sediment depth (m)
LOCH-1A	44°16.844′ S	169°54.036′ E	101	20	60.2
LOCH-1B	44°16.872′ S	169°54.027′ E	101	29	82.3
LOCH-2A	44°16.789′ S	169°55.430′ E	68	14	43.0
LOCH-2B	44°16.790′ S	169°55.440′ E	68	14	43.6

maximum 3 m ahead of the bit. An integrated bypass head was used to indicate when full stroke was achieved. The drill string was then pulled back 3 m, lifting the sample tube out of the sediment and into the borehole. The entire inner assembly was then retrieved via wireline to the deck of the barge where the core tube was removed. While the HPC was being reset, the core barrel was advanced to the depth reached by the piston corer on its previous stroke. The HPC was redeployed and the process repeated. Each 3 m coring run took between 30 and 45 min and drilling operations were carried out around the clock.

Core liner containing recovered sediment was removed from the HPC and transferred to the tender (RV *Beryl Brewin*), where it was cut into two 1.5 m sections and capped. Sections that contained significant biogenic gas (methane) were perforated with a hand-held electric drill. Cores were left to rest for up to 10 min, were placed in custom plywood boxes, and were transported to the jetty at Port Bryson onboard a 4.4 m alloy support vessel (Fig. 4). Shore-based staff collected the core from the jetty and drove it to a temporary field facility located above the control gate at the outlet to the Ohau canal (Fig. 1). The field facility included a refrigerated shipping container and portable office/lab. X-ray images of each core section were collected using a Ectotron portable system with a digital radiography plate. Images were used to examine core quality and results were reported via very high-frequency (VHF) radio to the tender vessel and passed to the head driller. Finally, core sections were placed into a storage rack system in the refrigerated shipping container.

The coring system performed exceptionally well and achieved near-complete sediment recovery in all four holes. Loss of up to 10 cm between coring runs occurred in each hole, but these gaps were covered via a two-hole offset coring at each site (Fig. 5). A splice for each site will be established using X-ray CT data. Recovery of diamicton at the base of the targeted sedimentary section was achieved at LOCH-1 and -2. Basic drill site information and coring outcomes are listed in Table 1. Full recovery of offset cores was achieved at LOCH-2. While we were unable to penetrate a stiff interval at 60 m below the lake floor in LOCH-1A, recovery of the full 80 m thick sedimentary sequence was achieved in LOCH-1B.

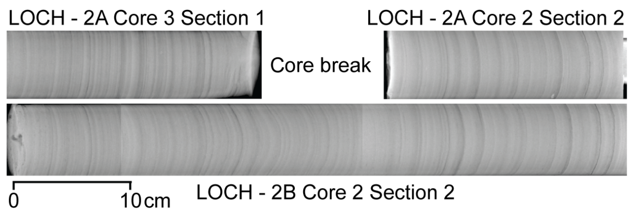

Figure 5. X-ray images showing 10 cm core loss at run break in LOCH-2A and recovery of the missing section in offset hole LOCH-2B (up to right). Distinct layers can be correlated between cores at mm scale from each site using visual and statistical techniques.

5 Post drilling analysis and preliminary results

5.1 Non-destructive continuous measurements

Core was transported in a refrigerated shipping container to a core facility located in the Geology Department at the University of Otago, Dunedin, New Zealand. Physical properties data including gamma-attenuation density, compressional (P)-wave velocity, and volume-specific magnetic susceptibility were collected on whole core using a Geotek multi-sensor core logger. X-ray computed tomography (X-ray CT) scans were obtained on whole cores at the Innervision Ltd CT facility at AgResearch, Mosgiel, New Zealand, using a GE Brightspeed medical X-ray CT scanner. We used these high-resolution data to establish a near-continuous (600 µm resolution) density data series through regions of the core that were distorted due to biogenic gas bubbles. These data series are required to establish an annual layer count for the sedimentary record. Additional data including resistivity, high-resolution infinite volume magnetic susceptibility, colour spectrophotometry, and RGB line scan images were collected from the Geotek system once the cores were split. U-channel samples were then taken from one half and natural remanent magnetization intensity, inclination and relative declination and anhysteretic remanent magnetization were acquired every 1 cm using a 2G Enterprises superconducting rock magnetometer at the University of Otago. Continuous μXRF data are also being collected from the u-channels at mm-scale resolution using an ITRAX housed at the Korea Polar Research Institute.

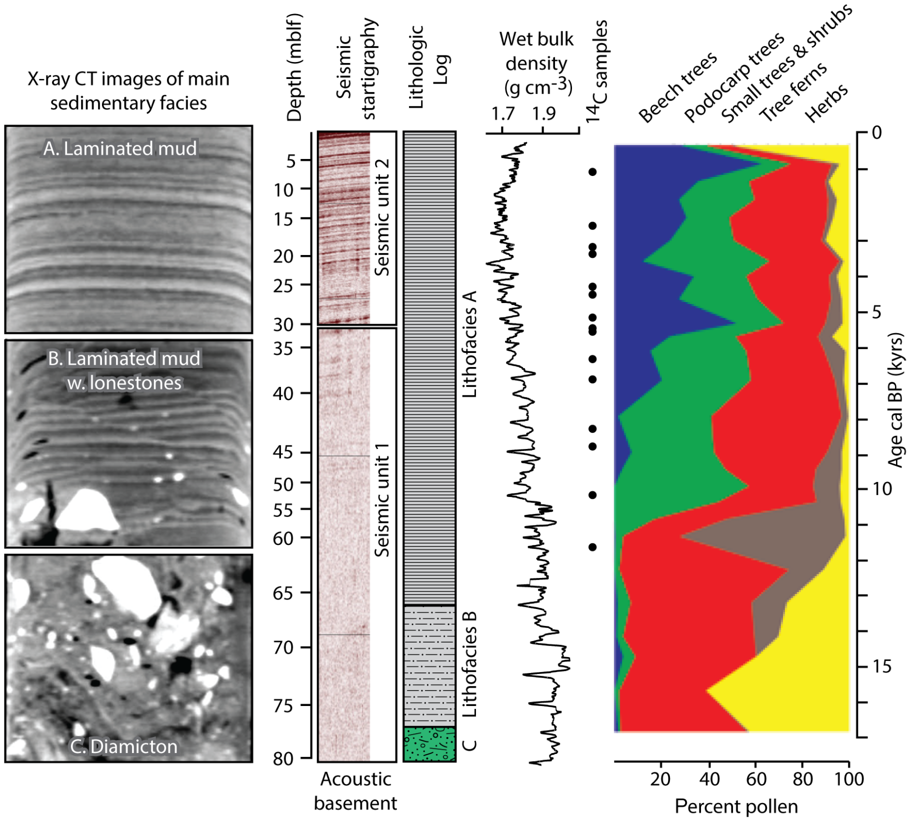

Figure 6. X-ray CT images of three primary facies recovered at LOCH-1 and -2. Seismic facies, basic stratigraphic column, and smoothed wet bulk density data from LOCH-1. Density minima every 1.5–3 m indicate core/section breaks. Pollen changes observed in core catcher samples from LOCH-1 showing a LGM to Holocene vegetation transition consistent with that observed at other sites in New Zealand. Preliminary ^{14}C samples (black dots) and associated age data align well with the age distribution inferred from pollen biostratigraphy.

5.2 Sedimentology, stratigraphy, paleontology, and geochemistry

Diamicton occurs at the base of the sedimentary sequences recovered at LOCH Sites 1 and 2 (Fig. 6) and likely represents subglacial or grounding zone proximal till deposited at the Last Glacial Maximum or during a phase of rapid retreat of the Ohau Valley glacier between 17 900 and 17 500 years ago (Putnam et al., 2013). Laminated sediments with occasional lone stones occur up to 4 m above the basal diamicton at LOCH Site 2 and 9 m at the LOCH Site 1 (Fig. 6). Laminated muds dominate the remaining sedimentary section at each site and offer potential for an unprecedented record of climate variability from the late glacial through the Holocene at decadal to annual resolution. Lithologic data from LOCH-1 indicate that the transition between seismic units 1 (layered) and 2 (opaque) at 30 m below the lake floor does not coincide with a change in facies or significant environmental transition (Fig. 6). However, an increase in core disturbance due to biogenic gas escape occurs at and below this depth and suggests that the change in seismic character corresponds to the depth at which in situ biogenic activity, and related methane gas production, increase.

Preliminary micropaleontological analyses have been completed on core catcher material from both drill sites. The lowermost laminated sediments contain a typical late glacial pollen assemblage, which transitions up core through a typical New Zealand deglacial sequence (Fig. 6) (e.g. Vandergoes et al., 2008, 2013). Diatom concentration is very low at the base of the sedimentary sequence, but increases in the Holocene interval. Sixty-nine species from several genera, including *Discostella*, *Cyclotella*, *Fragilaria*, *Achnanthidium*, and *Lindavia*, have been identified so far. Twenty-six radiocarbon dates have been generated from terrestrial and aquatic macrofossils and indicate ages that are consistent with our preliminary pollen biostratigraphy and layer counts (Fig. 6).

5.3 Future work

A core workshop was held at GNS Science on October 2016 and analysis of data continues today. Our team is developing plans to establish a latitudinal transect along New Zealand to core several lake systems in the North and northern South islands to examine environmental response to changes in the position of the westerlies and the impact on rainfall distribution. A major goal is to integrate these new high-resolution datasets from New Zealand with ice core and sediment records from the south-western Pacific and Ross Sea sectors of Antarctica (e.g. Bertler et al., 2018; Escutia et al., 2003) to reveal details regarding climate system evolution in the Southern Hemisphere as Earth's surface temperatures increased over the past 20 000 years.

Data availability. Preliminary data outlined in this progress report are not publicly available as they are still being evaluated by the LOCH project team. Fully vetted datasets from the LOCH cores will be made available when scientific papers and reports are published.

Author contributions. RL, GD, and MV lead the LOCH project and are involved in all aspects from lake monitoring to sediment core analysis. All authors contributed to the design and implementation of various aspects of the field operation and/or data acquisition phase. RL, AP, and TK wrote the original version of this paper, which was refined by GD, MV, JH, and AF. AG and PU designed and ran the high-resolution seismic survey. JH and SF conducted chirp surveys and collected Mackereth cores. JH and MV acquired X-ray CT data. AF and RC conducted the bathymetric survey and acquired and interpreted acoustic Doppler current profile data with GS. HR analysed short cores and monitoring data as part of her PhD project. SW contributed to the lake monitoring programme and helped acquire lake column turbidity data. BD was head curator and acquired physical property data. ML acquired preliminary μXRF data. FN, PL, GW, and FF conducted paleomagnetic analysis. LC acquired diatom data. XL conducted palynological analysis. TK and AP led the drilling operation and GB, MC, MH, EK, SL, DM, CM, PM, PD, CR, PR, DS, and MT were members of the drilling and/or drill site management team.

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

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Scientific Drilling
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Preparing for the new age of the Nagoya Protocol in scientific ocean drilling

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Abstract. Deep biosphere research has become one of the major scientific focuses in ocean drilling science. Increased scientific attention to microbiological research of the subseafloor environment raises the complications and concerns related to adherence to the Nagoya Protocol of the Convention on Biological Diversity (CBD). The Nagoya Protocol's implementation has prompted new legislation that could change international collaborative research on the geomicrobiology of the subseafloor. In this paper, we summarize the central points of the Nagoya Protocol on access and benefit-sharing (ABS) and discuss their relationship to ocean drilling research. In addition, we addressed the challenges faced by ocean drilling in complying with this international convention.

1 Introduction

In recent decades, deep life has become one of the major research themes of scientific ocean drilling. An increasing number of expeditions have conducted fruitful deep biosphere research. Cross-national collaboration in the field is very common, as most ocean drilling expeditions are conducted via international programs (Oldham et al., 2014). Since the adoption of the Nagoya Protocol, the legality of using genetic resources obtained through drilling core samples for research, especially in international collaborations, requires reconsideration. Prior to the commencement of the Convention on Biological Diversity (CBD) in December 1993, biological samples were relatively easy to use for research purposes. Previous regulations primarily focused on customs control for taxation purposes, or plant quarantine guidelines to prevent the introduction of undersired species. Both types of regulations also applied to core samples obtained from land, when the samples were transferred abroad after drilling. Samples obtained from drilling in the ocean, however, were not subject to either type of regulation.

The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization, known by its simplified name "the Nagoya Protocol", was approved by the Conference of the Parties to the CBD in October 2010 (Table 1). The CBD was drafted and agreed upon by the United Nations Conference on Environment and Development and was signed by diverse parties throughout the world. The vast majority of the world's governments committed to abiding by and enforcing the CBD. The aim of the CBD is to promote "sustainable development" of biological diversity, namely "meeting our needs while ensuring that we leave a healthy and viable world for future generations" (Secretariat of the Convention on Biological Diversity, 2010). After discussion and negotiation for over 10 years by multiple working groups mandated by the CBD, the Nagoya Protocol was adopted in 2010, and entered into force on 12 October 2014, 90 days after the 50th instrument of ratification was deposited (see the Nagoya Protocol website in Table 1). As of the end of May 2018, 92 countries have become signatories and 105 countries have ratified the Nagoya Protocol (Table 1).

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Table 1. Useful URL links are provided for scientists to seek detailed information. Abbreviations are listed in Appendix A.

Useful links to seek information	
CBD	https://www.cbd.int/
Nagoya Protocol	https://www.cbd.int/abs/
The Bonn Guidelines	https://www.cbd.int/doc/publications/cbd-bonn-gdls-en.pdf
ABS Clearing-House	https://absch.cbd.int/
WFCC Guidelines	http://www.wfcc.info/index.php/guidelines/
IODP	https://www.iodp.org/
DeepBIOS website in KCC	http://www.kochi-core.jp/DeepBIOS/
IODP sample database for microbiological samples	http://www.iodp.org/resources/access-data-and-samples
ABS regulation in the EU	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52012SC0292
ABS Guidelines in Japan	http://www.env.go.jp/nature/biodic-abs/english.html
UNCLOS	http://www.un.org/Depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

As one the CBD's three main established goals, the Nagoya Protocol specified the utilization of genetic resources. The Nagoya Protocol affirmed states' sovereign right to control the utilization of their genetic resources. In particular, by establishing more predictable conditions for accessing genetic resources, the Nagoya Protocol improved legal certainty and transparency for both resource providers and users. The document also helps to ensure benefit sharing when genetic resources leave the country of origin. Finally, the protocol lays out core obligations for its contracting parties to take measurements related to genetic resource access, benefit sharing, and compliance. Under the Nagoya Protocol, obligations to share benefits require potential users to seek prior informed consent (PIC) and negotiate mutually agreed terms (MATs) with the provider's government or local individuals. The Bonn Guidelines on access and benefit-sharing (ABS), drafted by the secretariat of the CBD, provide information on the terms that must be negotiated between the user and provider, and recommend the contents be finalized in MATs (Table 1). Contracting parties of the Nagoya Protocol are additionally required to quantify metrics related to providing, accessing, using, and monitoring their genetic resources.

As more countries ratify the Nagoya Protocol, many states have also established their own similar guidelines or regulations. Access to most of these governmental policies can easily be obtained through the ABS Clearing-House website (Table 1). These systems have led to the wide dissemination of related guidelines within global scientific communities. For example, the code of conduct and best practice of the Global Genome Biodiversity Network (GGBN) was modeled after the Nagoya Protocol on ABS (GGBN Guidance, 2015). The World Federation for Culture Collections (WFCC) has declared that the process of isolation, handling, storage, and distribution of microorganisms and cell cultures must be carried out safely and in compliance with relevant legislation, regulation, and international conventions (see WFCC website in Table 1). The Microbial Resource Research Infrastructure (MIRRI) program has developed strategies and tools to comply with the Nagoya Protocol and established a best practice manual based on ABS (Verkley et al., 2016). An increasing number of universities and research institutions have begun to prepare policies to accompany their countries' guidelines.

Like every other international treaty, the Nagoya Protocol is imperfect. The scientific community has raised objections to several aspects of the CBD. A recent paper published in *Science*, which gathered signatures of 172 scientists from 35 countries, listed the obstacles that the CBD imposes on research, and stated emphatically that scientists cannot conduct biodiversity research unless they have access to the resources they seek to study, and the ability to share those resources and their expertise among countries (Prathapan et al., 2018). The authors further urged the Conference of the Parties of the CBD to recognize the problem and to establish legal mechanisms to enable biodiversity research of relevance to conservation (Prathapan et al., 2018). In popular commentary following publication of this article, news articles identified that country frameworks and legal facility buildings to implement the Nagoya Protocol are key problems (Prathapan et al., 2018; Pisupati, 2018). Despite the positive intentions of the Nagoya Protocol, vague definitions of genetic resources, lack of legal clarity and coordination in most of the countries, and complex regulations affecting the transfer of biological material still plague its implementation (Neumann et al., 2017; Blasiak et al., 2018; Prathapan et al., 2018). Research utilizing foreign genetic resources faces increased hurdles. Specifically, international collaboration usually requires transfer of samples, which is complicated to implement under the Nagoya Protocol. Nevertheless, it is ultimately the responsibility of "users", namely the scientists themselves, to follow international treaties and laws of foreign countries. Moreover, the organizations that employ scientists should supervise scientists' behavior and protect scientists. We recommend that universities and research institutions seek information regarding the CBD and the Nagoya Protocol and consider building their own in-house best practice rules accordingly.

2 Nagoya Protocol with the Ocean Drilling Program

2.1 Utilization of genetic resources in ocean drilling science

The marine realm comprises 70 % of the surface of the biosphere and contains a rich variety of organisms, including at least 34 of the 36 living phyla, some of which are found exclusively in the oceans. Genetic resources from marine environments have been increasingly utilized, with applications in over 18 000 natural products (Arrieta et al., 2010). Furthermore, 4900 patents are associated with genes of marine organisms, with a rate of increase of 12 % per year (Oldham et al., 2014). Deep seabed ecosystems and their associated genetic resources offer great scientific potential. Research activities investigating deep subseafloor genetic resources are limited by technological capacity and by the financial resources required. International scientific collaboration such as the International Ocean Discovery Program (IODP) provides opportunities to access and take measurements of the deep subseafloor (Table 1).

The biosphere beneath the water column of the ocean was revealed to biologists after a successful expedition, Leg 201 of the Ocean Drilling Program (ODP). Research conducted on this expedition revealed the existence of a metabolic microbial ecosystem on the deep subseafloor (D'Hondt et al., 2003, 2004). Since then, scientists have progressively revealed more of the significant biomass, biodiversity, and functions of microbial cells in the deep biosphere, with scientific publications on the topic increasing annually (Parkes et al., 1994; D'Hondt et al., 2004; Lipp et al., 2008; Kallmeyer et al., 2012). Conducting research on genetic resources, including through the application of biotechnology, is considered "utilization of genetic resources", according to Article 2 of the Nagoya Protocol (Table 1). "Biotechnology", as defined in the convention, means any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for a specific use (see the Nagoya Protocol website in Table 1). According to this clause, geomicrobiological research conducted by ocean drilling programs accesses and utilizes genetic resources on the subseafloor.

Utilization of core material obtained through ocean drilling as a genetic resource is technically different than other types of research and the sampling procedure is more complicated. In general, one drilling expedition can obtain hundreds of meters of core samples. In the case of microbiological research, however, specialized sampling methodologies are required because organisms and biological molecules such as DNA, RNA, and proteins can be damaged by exposure to unusual temperatures, oxidation, and air contamination during the drilling process. Therefore, DNA research requires core samples to be deep-frozen for storage, while research targeting living cells requires more complicated storage treatment of samples (e.g., anaerobic or high-pressure conditions). Moreover, the sampling process for these experiments usually requires aseptic conditions to avoid contamination. In the current and past ocean drilling programs, some expeditions have included deep biosphere research as a major component of the original proposal (expeditions listed in Table 2). In all other cases, the collection of deep biosphere samples during an expedition is contingent on the applications (sample requests) for such samples, and/or the participation of microbiologists. We surveyed accessible databases of the current and past ocean drilling programs and found that 53 expeditions (including the nine expeditions in Table 2) included microbiologists among the science party, which allowed microbiological samples to be collected during the expedition. Besides samples collected on these expeditions, as explained above, the hundreds of kilometers of split-core samples that are stored in 4° C refrigerated core repositories (see IODP website in Table 1) are rendered useless for microbiological research because of the severe sample condition requirements of core samples for subsequent microbiological research. In order to expand the utilization of core samples for post-cruise research, the Kochi Core Center began curating deep-frozen core samples (Masui et al., 2009). Samples from 11 drilling expeditions in the Deep BIOsphere Sample (DeepBIOS) database are available to scientists upon request (see DeepBIOS database in Table 1), while other core repositories have also stored deep-frozen core samples (see IODP website in Table 1). These samples are available to scientists by application after the expedition moratorium. Accordingly, IODP samples can be obtained in two ways: by participating in drilling expeditions and/or by requesting samples from core repositories. All core samples and sample requests are managed through a curation system run by the science operators of the IODP.

2.2 Controversial points of the Nagoya Protocol for ocean drilling programs

Marine scientific research, including ocean drilling, is impacted by the United Nations Convention on the Law of the Sea (UNCLOS), which outlines the extent of states' sovereignty in the sea bed and subsoil of the territorial sea, the contiguous zone, and the sovereign right of states to an exclusive economic zone (EEZ) (see UNCLOS website in Table 1). Consequently, to drill within an EEZ, scientists

Table 2. List of ocean drilling expeditions that included deep biosphere research as a major scientific objective in their drilling proposals. Expeditions conducted by three drilling platforms from the Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program are listed. EEZ: exclusive economic zone.

Expeditions	Drilling vessel	Year	Drilling location
Leg 201: Controls on Microbial Communities in Deeply buried Sediments, Eastern Equatorial Pacific and Peru	*JOIDES Resolution*	2001	EEZ
Exp. 329: South Pacific Gyre Microbiology	*JOIDES Resolution*	2006	International waters
Exp. 336: Mid-Atlantic Ridge Flank Microbiology: Initiation of long-term coupled microbiological, geochemical, and hydrological experimentation within the seafloor at North Pond, western flank of the Mid-Atlantic Ridge	*JOIDES Resolution*	2010	International waters
Exp. 366: Mariana serpentinite mud volcanism: geochemical, tectonic, and Biological processes	*JOIDES Resolution*	2016	International waters
Exp. 331: Deep Hot Biosphere	*Chikyu*	2010	EEZ
Exp. 337: Deep Coalbed Biosphere off Shimokita: Microbial processes and hydrocarbon system associated with deeply buried coalbed in the ocean	*Chikyu*	2012	EEZ
Exp. 370: T-Limit of the Deep Biosphere off Muroto (T-Limit)	*Chikyu*	2016	EEZ
Exp. 347: Baltic Sea Basin: paleoenvironmental evolution of the Baltic Sea Basin through the last glacial cycle	Mission Specific	2013	EEZ
Exp. 357: Atlantis Massif Serpentinization and Life: Microbiological, alteration, and tectono-magmatic processes in young mafic and ultramafic seafloor	Mission Specific	2015	International waters

must apply for marine scientific research (MSR) clearance to the country sovereign over the EEZ, whereas drilling in international waters does not require MSR clearance. Research targeting the deep biosphere (e.g., studies of DNA diversity or cell extraction) inevitably must access genetic resources from the country of origin. Interpreting the Nagoya Protocol becomes difficult in this context because the national regulations required by the Nagoya Protocol vary according to the country of origin of the genetic resource. The current members of the IODP have different statuses with respect to their adherence to the Nagoya Protocol. Japan, India, South Korea, China, and the European Union have ratified the Nagoya Protocol; Brazil and Australia are only signatories; New Zealand and Canada are parties to the CBD but are not parties or signatories of the Nagoya Protocol; and the United States of America is not a party to the CBD. The European Union has implemented regulations, and Japan has also established a national guideline (sea EU regulation and Japanese guideline links in Table 1). Though Brazil, Australia, and New Zealand are not parties to the Nagoya Protocol, they nevertheless have individual legal frameworks to implement ABS legislation for genetic resources. Moreover, regardless of whether the users' countries have ratified the Nagoya Protocol, scientists and their collaborators working with core samples containing DNA and microbes originally extracted from areas under other national jurisdictions are required to follow the regulations of the provider countries. Naturally, the same regulations apply to continental drilling programs. We summarized drilling locations of the past expeditions that comprised deep biosphere research as a major scientific object (Table 2). Five of the expeditions obtained samples from EEZs and four obtained samples from international waters. In addition, 21 of the 53 expeditions that included microbiologists in the science party conducted drilling in EEZs. Both EEZs and international waters are important for scientific reasons; sediments from EEZs are close to shore and are usually rich in organic matter, which is linked to higher microbial biomass, whereas locations further from shore, such as international waters, tend to have oxygen down through the deep sediments (Kallmeyer et al., 2012; D'Hondt et al., 2015). Roughly half of the previous drilling expeditions included deep biosphere research drilled within EEZs. Therefore, it is important for microbiologists to determine ABS regulations of the EEZ country very early in their expedition preparations.

Furthermore, the timing of the sample's extraction is also a key issue to consider. For example, core samples for analyzing DNA were obtained from EEZs of Peru and Ecuador during Leg 201 in 2002, but the Nagoya Protocol was only ratified in those countries in 2014 and 2017, respectively

(D'Hondt et al., 2003). Peru established subsequent restrictive legislation in 2014 (https://absch.cbd.int/countries/PE/MSR, last access: June 2018), but Ecuador, thus far, has not. Although the scope of the Nagoya Protocol is not retroactive, several countries apply its terms on benefit sharing to continuing and new uses of genetic resources. A similar example relates to core samples that were obtained in 2013 from the EEZ of Denmark and Sweden during Exp. 347. These samples were collected prior to the EU regulation of 2014 that declared the Nagoya Protocol effective (The European Parliament and the Council of the European Union, 2014). Whether the rights outlined in the Nagoya Protocol extend to past expeditions must be assessed case by case.

2.3 Implementation of the Nagoya Protocol

Since the Nagoya Protocol came into effect, PIC and MAT applications have been required in addition to MSR clearance when drilling occurs in another country's EEZ. Principal investigators of deep biosphere research will require assistance from the science operators of the drilling vessels due to the potentially complicated legal requirements associated with application for ABS. Countries of origin may require detailed information on access to genetic resources, namely the extraction time, drilling location, and sampling quantities, far in advance of the expedition, which burdens scientists who apply independently. Managing the utilization of the genetic resources through the IODP, however, is much simpler than gaining access. A highly advanced system has already been developed by IODP curators to manage sample requests and trace genetic resources. All core samples are identified by location and depth and provided in response to a sample request. A material transfer agreement (MTA) form is recommended to help science operators manage the transfer of biological samples. The "IODP Sample, Data and Obligation Policy" already requires the publishing of data obtained utilizing IODP samples (http://www.iodp.org/top-resources/program-documents/policies-and-guidelines, last access: July 2018), thereby meeting the compliance obligations of the Nagoya Protocol for monitoring the utilization of genetic resources after they leave the source country. The situation of implementing the Nagoya Protocol and the time required for obtaining necessary legal clearance varies among countries. For instance, Japan's guidelines and the EU's regulations claim that no PIC is needed for scientific research of their genetic resources (see links in Table 1). India and Vietnam do not allow access to their genetic resources without prior applications to their governments (Ministry of Environment of Japan, 2018a, b). In general, it can take up to several months to obtain ABS permissions, which needs to be taken into account from the early stages of expedition planning.

2.4 Future concerns

Firstly, the Nagoya Protocol addresses ABS for genetic resources within national waters, while currently there is no such mechanism for genetic resources from the areas beyond national jurisdiction (ABNJs). The UN has continuously negotiated the "packaged" issue in multiple meetings including at the Biological Diversity of the ABNJ (BBNJ) Working Group (2006–2015), Preparatory Committee (2016–2017), and BBNJ treaty negotiations that began in September 2018. The reports of those meetings show that there was discussion for some form of benefit sharing for exploring genetic resources in the ABNJ, together with management tool building (Earth Negotiations Bulletin, 2018). The conclusion of the negotiations will most likely be to develop an international legally binding instrument under the UNCLOS for the conservation and sustainable use of marine biological diversity of ABNJ (United Nations Environment Programme, 2016). Therefore, the future scope of the CBD and the Nagoya Protocol may be extended to include the ABNJ of the UNCLOS, and such a global ABS measure would conceivably affect all scientific drilling expeditions (Rochette et al., 2015). Regardless of whether drilling occurs in the EEZ or in the ABNJ, researchers will need to obtain some form of consent to conduct deep biosphere research prior to undertaking expeditions, and this consent will require benefit-sharing agreements for after the research is completed. Ultimately, principal investigators of deep biosphere research will have to engage with global ABS regulations, including the Nagoya Protocol and the new treaty on the ABNJ of the UNCLOS.

Secondly, questions remain regarding the types of information on genetic resources that might be included in the scope of the Nagoya Protocol. Nucleic acid sequence reads and associated data as well as information on sequence assembly, annotation, and genetic mapping, which may describe up to an organism's whole genome, are suggested for inclusion as genetic resources, according to the report of the Ad Hoc Technical Expert Group on Digital Sequence Information on Genetic Resources (2018). Furthermore, metagenome sequencing of the deep seabed or sea water could be included in the scope of the Nagoya Protocol. In response to this possible hurdle, the Alliance of Science Organizations in Germany strongly cautioned against expanding the scope of the Nagoya Protocol to include digital sequence information (Alliance of Science Organizations in Germany, 2018). The massive growth in our life science knowledge base depends largely on the free and open availability of digital sequence information. Restriction of access to digital sequence information would significantly impair scientific progress. It is important for scientists to be aware of political limitations on their research activities.

3 Tentative implementation in JAMSTEC

Scientists of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) are told to consult the administration office nearly 2 years prior to conducting field research in EEZs or on land of other countries. The administration office (and outsourcing law office as needed) assists scientists in obtaining permissions for MSR, ABS, or any other necessary legislation. In addition to its role as a “user” of genetic resources, JAMSTEC also functions as a “provider” of such resources. JAMSTEC’s drilling vessel (DV) *Chikyu* has riser drilling equipment, which enables it to drill deeper than any other scientific drilling vessel. *Chikyu* has served as an official vessel in the IODP since 2007. To date, all IODP expeditions conducted by DV *Chikyu* drilled within the Japanese EEZ. Genetic resources extracted by *Chikyu* have been distributed worldwide under the IODP framework. Samples have been utilized for onboard distribution, and through secondary distribution in response to sample requests to the Kochi Core Center (see DeepBIOS website in Table 1). To adhere to the Nagoya Protocol, JAMSTEC established the Guidance on Access and Benefit Sharing on Subseafloor Genetic Resources from DV *Chikyu* and drafted a MTA for IODP expeditions in 2016. Ownership of the samples was claimed by JAMSTEC, and agreements on utilization and related intellectual property were established in the MTA. The IODP manages distribution and utilization of the core samples under the supervision of its “IODP Sample, Data, and Obligation Policy”. The MTA for genetic resources taken by DV *Chikyu* was drafted to meet the requirements of stakeholders of both the IODP and the Nagoya Protocol frameworks. In its guideline, Japan has decided that no PIC is required for accessing genetic resources from Japan, and the Japanese government encourages research institutions to take measures to govern their own genetic resources, in a similar vein to the EU regulation (see links to Japanese guidelines and EU regulation in Table 1). JAMSTEC will seek PIC when DV *Chikyu* drills in other countries’ territorial waters or EEZs and will take any additional action required by their research partners. This scenario will necessitate further contracts between JAMSTEC and foreign scientists regarding distribution of the core samples for biological research.

4 Summary

Scientific ocean drilling began as a research tool for fundamental geological research and has been crucial for attaining significant geological and geochemical findings as well as technological developments. Deep biosphere research developed quite recently but has grown significantly in recent decades. As a result of data collected from international ocean drilling expeditions and data benefit sharing, considerable achievements have been made in understanding the extensive subseafloor biosphere. The Nagoya Protocol is an international agreement that aims to guide countries in developing standard protocols and protections for accessing biological materials, and sharing the benefits derived from their utilization. Since its commencement, the Nagoya Protocol has placed international biological research, especially fieldwork, under greater political scrutiny and increased its complexity due to the variation in implementation between nations. Researchers and science operators must study and comply with permitting requirements for the countries in whose EEZ they plan to drill. Updated information on emerging legislation and regulations applicable to genetic resource usage is available for curators and staff participating in scientific drilling programs on the ABS Clearing-House website (Table 1). Crucially, potential users, particularly microbiologists, must communicate with officials responsible for implementation of ocean drilling programs to ensure that their requirements for necessary ABS measures and the related scientific importance are clear, protected, and attainable.

We will monitor the progress of the UN’s new treaty regarding ABNJ and report new information in future articles as it becomes available.

Data availability. Data are available on request from the corresponding author.

Appendix A: List of acronyms

ABNJ	Area beyond the national jurisdiction
ABS	Access and benefit sharing
BBNJ	Biodiversity beyond national jurisdiction
CBD	Convention on Biological Diversity
EEZ	Exclusive economic zone
EU	European Union
IODP	International Ocean Drilling Program/International Ocean Discovery Program
MAT	Mutually agreed terms
MTA	Material transfer agreement
NP	Nagoya Protocol
ODP	Ocean Drilling Program
PIC	Prior informed consent
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea

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Scientific Drilling
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Workshop Reports

Developing community-based scientific priorities and new drilling proposals in the southern Indian and southwestern Pacific oceans

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Abstract. An International Ocean Discovery Program (IODP) workshop was held at Sydney University, Australia, from 13 to 16 June 2017 and was attended by 97 scientists from 12 countries. The aim of the workshop was to investigate future drilling opportunities in the eastern Indian Ocean, southwestern Pacific Ocean, and the Indian and Pacific sectors of the Southern Ocean. The overlying regional sedimentary strata are underexplored relative to their Northern Hemisphere counterparts, and thus the role of the Southern Hemisphere in past global environmental change is poorly constrained. A total of 23 proposal ideas were discussed, with ~ 12 of these deemed mature enough for active proposal development or awaiting scheduled site survey cruises. Of the remaining 11 proposals, key regions were identified where fundamental hypotheses are testable by drilling, but either site surveys are required or hypotheses need further development. Refinements are anticipated based upon regional IODP drilling in 2017/2018, analysis of recently collected site survey data, and the development of site survey proposals. We hope and expect that this workshop will lead to a new phase of scientific ocean drilling in the Australasian region in the early 2020s.

1 Introduction

The importance of the Southern Hemisphere in the narratives of global plate tectonics and oceanography is well established, but understudied. This is in large part due to the vastness of the eastern Indian Ocean, southwestern Pacific Ocean, and the Indian and Pacific sectors of the Southern Ocean. This is an ideal region to address many of the 14 science challenges in the 2013–2023 IODP science plan. The Australian and Indian continents have undergone the largest and most rapid paleo-latitudinal shifts of any continents globally since 150 Ma. The region boasts the following: (i) arguably the greatest diversity of subduction zones from fully seismically coupled to uncoupled; (ii) extensive shallow marine seas and submerged continents (e.g., Zealandia) with extraordinary and unstudied stratigraphic records; and (iii) the largest suite of plume-related products and the largest mantle cold spot. Sampling of plateaus, ridges, and their associated sedimentary strata will provide an enormous wealth of information about their origin and address fundamental paleoceanographic and paleoclimate questions. Drilling of the Antarctic margin in the Indian Ocean and South Pacific sectors will increase our understanding of the Antarctic cryosphere and global climate evolution and past land and sea ice extent from the Cretaceous through the Cenozoic. Geomicrobiological questions can be addressed on a number of expeditions, including targeted expeditions to study the deep biosphere in a variety of tectonic settings. Petrological and geochemical studies of oceanic, back-arc and arc crust, as well as uplifted mantle remain a high priority, as do those of geological hazards.

To facilitate and nurture cross-disciplinary proposals, workshop breakout sessions focused on distinct tectonic settings and their associated paleo-environmental evolution. These included (1) large igneous provinces and associated paleoceanography, (2) subduction zones and associated paleoceanography, (3) a separate focus group on the Hikurangi subduction zone, (4) conjugate margin/Zealandia studies and associated paleoceanography, and (5) a biosphere frontiers subgroup meeting not related to the above tectonic settings. The potential proposals discussed in the breakout sessions are listed in Table 1, and locations shown in Fig. 1.

2 Large igneous provinces and associated paleoceanography

Earth's evolution includes multiple, geologically brief episodes when extraordinary volcanism occurred across some surface regions. Documentation for this comes from large igneous provinces (LIPs), extensive areas covered by thick layers of mostly mafic material that was emplaced on million-year timescales. While LIPs have been widely acknowledged and discussed by the geoscience community for more than two decades, major first-order questions regarding their origin and environmental impact remain. Profound and rapid changes in biota and chemical cycling have also punctuated Earth's history and many of these "events" have been linked to the formation of LIPs. For example, massive volcanic outpouring may have been coupled to large increases in atmospheric $p\mathrm{CO}_2$, which could have raised surface temperatures, amplified the hydrological cycle, and changed ocean circulation. Equally important is the fact that oceanic LIPs typically lie above the carbonate compensation depth, thereby providing the elevated foundation on which many outstanding records of Earth's climate history accumulate.

2.1 Manihiki-Plus: ground zero for understanding large igneous provinces and their environmental impact

Manihiki Plateau, in the southwestern Pacific, is a large ($770\,000\,\mathrm{km}^2$) bathymetric high, which appears to have been emplaced about 125–120 Ma. Five drill sites are proposed, four on Manihiki Plateau and one on the older Magellan Rise. Numerous hypothesis could consequently be addressed: (1) Manihiki Plateau was part of a much larger LIP that has been disjointed since the Cretaceous (other components are believed to include the Ontong Java and Hikurangi

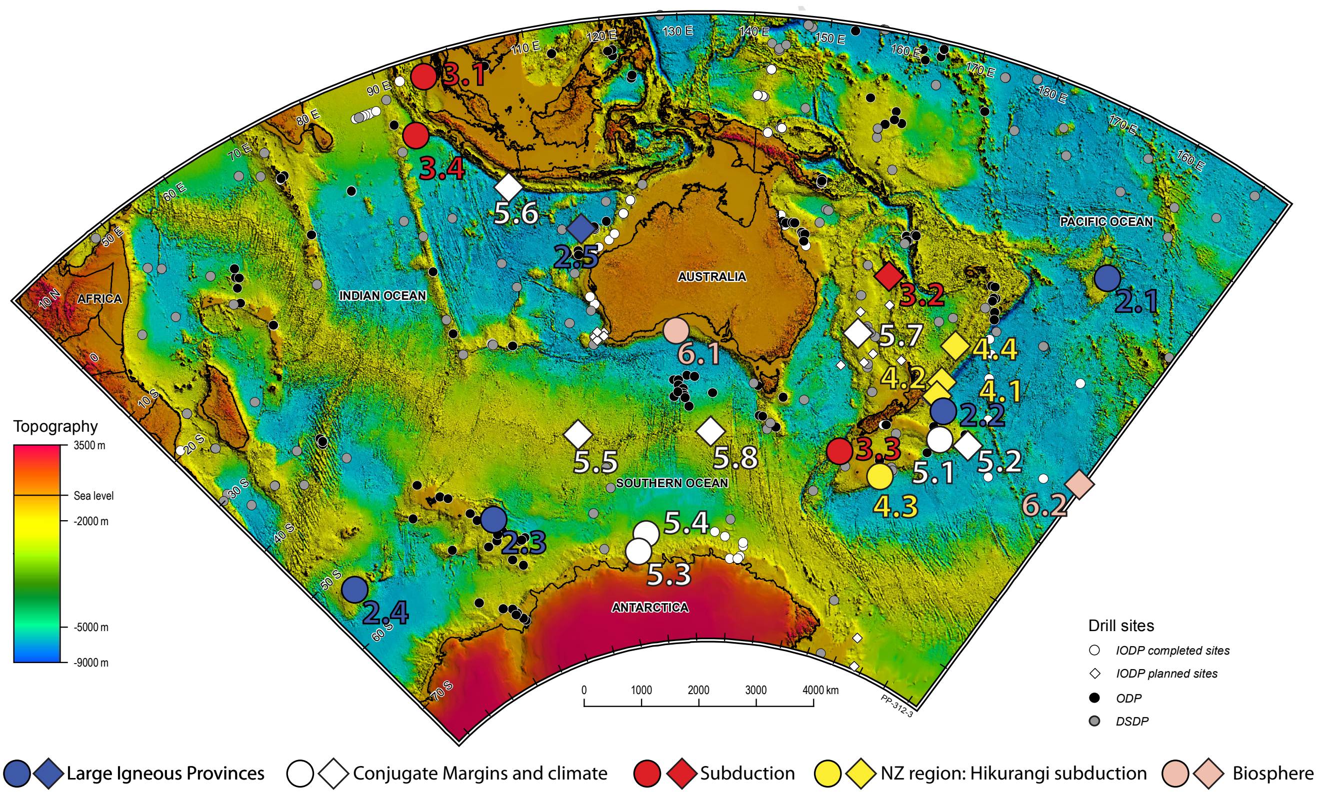

Figure 1. Location map of potential proposals discussed in the workshop, with color-coded dots denoting the main theme for each proposal. Small colored circles indicate previous (and planned) drilling by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and IODP. Larger circles and diamonds are projects discussed in the meeting and are colored by theme, and numbered according to sections discussed in text. Large circles indicate proposals that appear mature enough to develop pre-proposals. Large diamonds require site survey proposals to be developed, or are awaiting the results of upcoming drilling in the region (e.g., Hikurangi subduction zone and Lord Howe Rise regions) and may require a focus workshop to further refine hypotheses.

plateaus); (2) the environmental impacts of LIP emplacement can be monitored by syn-LIP sedimentation at proximal older locations, especially Magellan Rise; and (3) the sedimentary records on top of Manihiki Plateau and Magellan Rise hold the paleoceanographic history of the Central Pacific from the Late Jurassic to present, as the two locations lie beneath the eastern end of the Pacific warm pool.

2.2 Hikurangi Plateau large igneous province

Drilling on the Hikurangi Plateau will yield insights into the mantle source and LIP emplacement rates, and help to constrain geodynamic models and environmental impacts of LIP emplacement. It will also enable testing of the hypothesis that Ontong Java, Manihiki, and Hikurangi were once part of a single super-LIP, and will allow controls on subduction megathrust slip behavior to be studied. Upcoming drilling on IODP expeditions 372 and 375 will provide critical information to underpin the development of such a proposal, as will multichannel seismic reflection and refraction lines to be acquired in November/December of this year. It was suggested that the proponent group aim to develop a pre-proposal by October 2018, once all of the information is available and hypotheses could be fully formulated.

2.3 Kerguelen Plateau large igneous province emplacement and associated paleoceanography

A multidisciplinary drilling expedition on the Kerguelen Plateau will investigate LIP formation and Southern Ocean paleoceanography over the past 120 Ma. The Kerguelen Plateau incorporates multiple microcontinents, and has as unknown relationship to dipping reflection sequences on the nearby Antarctic margin. Tectonomagmatic questions include why the most voluminous magmatism appears to have post-dated continental breakup (unlike other flood basalts associated temporally with breakup), and how continental fragments were isolated in the plateau. Cretaceous and Cenozoic paleoceanographic records are well preserved in regional carbonates, and the complex topography of the Kerguelen Plateau exerts a strong influence on the pathways of water masses within the Antarctic Circumpolar Current (ACC) and

Table 1. List of proposals discussed in the workshop, lead contacts and current status for each proposal. Number relates to section number in main text.

Short title		Science lead(s)	Status
Large igneous provinces and associated paleooceanography			
2.1	Manihiki Plateau/Magellan Rise LIP	Gerald Dickens	Ready for pre-proposal
2.2	Hikurangi Plateau LIP	Christian Timm/Jörg Geldmacher	Site survey scheduled 2017
2.3	Kerguelen LIP	Gabriele Uenzelmann-Neben	Site survey scheduled
2.4	PePSI-SO (Conrad Rise)	Minoru Ikehara	Pre-proposal submitted 2017
2.5	Wombat Plateau	Jessica Whiteside	Site survey data required
Subduction inputs			
3.1	Andaman back-arc basin	Yatheesh Vadakkeyakath	Ready for pre-proposal
3.2	New Caledonia peridotitic ophiolite	Julien Collot	Focus workshop required 2018
3.3	Puysegur subduction initiation	Michael Gurnis	Site survey scheduled 2018
3.4	Sumatra intraplate earthquakes	Lisa McNeill	Ready for pre-proposal
Eastern NZ region (Hikurangi subduction zone, Canterbury Basin)			
4.1	Hikurangi subduction inputs	Ake Fagereng	Develop pre-proposal after IODP 372/375
4.2	Hikurangi slow slip fluid flow	Ingo Pecher	Develop pre-proposal after IODP 372/375
4.3	Canterbury Basin freshwater resources	Aaron Micallef	Ready for pre-proposal
4.4	Kermadec volcanism	Martin Jutzeler	Focus workshop required 2018
Conjugate margins			
5.1	Chatham Rise pockmarks and CO_2	Lowell Stott	Pre-proposal submitted Oct. 2017
5.2	Chatham Rise tectonics and climate	Karsten Gohl	Focus workshop required
5.3	Totten Glacier ice sheet evolution	Amelia Shevenell	Pre-proposal submitted Oct. 2017
5.4	Sabrina Coast slope deposits	Brad Opdyke	Ready for pre-proposal
5.5	SE Indian Ocean ridge geodynamics and climate	Dietmar Müller	Site survey data required
5.6	Indian Ocean dipole and monsoon	Sushant Naik	Site survey data required
5.7	Future Drilling in Northern Zealandia	Ron Hackney	Focus workshop required 2018
5.8	Australian-Antarctic transect	Peter Bijl	Site survey data required
Biosphere			
6.1	Great Australian Bight hydrogeology and biosphere	Ulrich Wortmann	Pre-proposal submitted Oct. 2017
6.2	South Pacific Gyre/Southern Ocean biosphere	Fumio Inagaki/Ann Dunlea	Site survey data required

the Antarctic Bottom Water (AABW). In the Cenozoic era, the pathways and intensities of Southern Ocean circulation were developed and significantly modified by emplacement of the Kerguelen Plateau and opening of regional tectonic gateways.

2.4 Plio-Pleistocene paleoceanography of the southwestern Indian sector of the Southern Ocean (PePSI-SO)

A preliminary proposal (918-Pre) to drill in the Conrad Rise and Del Caño Rise regions (Indian Ocean sector) of the Southern Ocean (SO) was submitted to IODP in April 2017. Five high sediment accumulation sites are proposed, with the aim to document Southern Ocean variability and atmosphere, ocean, and cryosphere interactions in the southwestern Indian Ocean sector. The targeted drill sites will fill important gaps in our knowledge covering the middle Miocene cooling (~ 14 Ma), late Miocene carbon shift (8–6 Ma), the Pliocene climate optimum (5.3–3.3 Ma), the late Pliocene global cooling (3.3–2.6 Ma), the mid-Pleistocene transition (MPT: 1250–700 ka), and the mid-Brunhes transition (~ 0.43 Ma). These sites will contribute to further understanding dynamic fluctuations of the ACC and associated meridional frontal migrations in relation to global circulation (e.g., Agulhas Leakage, and Atlantic meridional overturning circulation). Also investigated will be changes in interocean surface and deep-water transport, and past variability in southern Indian Ocean sea ice extent, with implications for air–sea gas exchange and the partitioning of CO_2 between the atmosphere and the ocean interior.

2.5 Wombat in the greenhouse: sampling rare Southern Hemisphere records of Mesozoic environmental change

It is proposed to drill Mesozoic sedimentary sequences on the northeastern Wombat Plateau, on the northernmost continental margin of Australia. Drilling during Ocean Drilling Program (ODP) Leg 122 in 1988 obtained a thick succession of Late Triassic deltaic and shallow marine sediments unconformably overlain by Late Cretaceous pelagic sediments, including records of Oceanic Anoxic Event (OAE) 2 and the Cretaceous–Paleogene boundary. However, recovery was poor in part and new core from the Wombat Plateau will provide a better understanding of early Mesozoic paleoclimate, paleoceanography, and paleoenvironments in the Southern Hemisphere. These sites should provide key Southern Hemisphere data for Late Triassic climate events, including the hypothesized late Norian–Rhaetian increase in atmospheric $p\mathrm{CO}_2$, Carnian pluvial event, two bolide impacts, and the far-field effects of the Central Atlantic magmatic province, a LIP contemporaneous with the end-Triassic mass extinction. Late Cretaceous sediments will provide an important deep-water record of dynamic environmental changes immediately prior to the end-Cretaceous mass extinction event.

3 Subduction zones

3.1 Andaman back-arc basin: understanding crustal accretion in a sedimented spreading region

The Andaman back-arc basin was formed by subduction of the Indian plate under the Burmese plate. Linear magnetic anomalies indicate that seafloor spreading in the Andaman basin commenced at ~ 4 Ma, but anomalies are lacking in some sectors. Drilling in the rift valley of the Andaman back-arc basin will provide important insights on crustal accretion and why pronounced linear magnetic anomalies are absent in this sedimented spreading. Drilling at the Alcock and Sewell seamounts and the inferred location of the oldest oceanic crust will help address several salient regional problems, such as the nature of the crust underlying the Alcock and Sewell seamounts, and the timing of formation and evolution of the Andaman back-arc basin.

3.2 Amphibious drilling of the New Caledonia peridotitic ophiolite, northern Zealandia

The geodynamic evolution of the southwestern Pacific, from Gondwana break-up during the Cretaceous to subduction-dominated tectonism in the Cenozoic, resulted in the obduction of a string of peridotite ophiolites/massifs from the Anita ophiolite in Southern New Zealand to the Papuan Ultramafic Belt ophiolite. The New Caledonian ophiolite is one of the largest obducted peridotitic masses in the world. An amphibious drilling proposal (ADP) will provide a more complete understanding of an obducted deep geological system from a terrestrial setting to its marine extension, which is as close as possible to its unobducted mantle lithosphere counterpart. Drilling onshore and offshore along the New Caledonia ophiolite will allow emplacement mechanisms of mantle-dominated allochthons to be assessed, as well as constraining high- and low-temperature alteration processes. Other objectives could relate to studying archaeal and eubacterial communities that are known to develop in these alkaline systems, while the formation of the world's second largest rimmed carbonate reefs during the Miocene to Quaternary will be investigated. Developing an ADP will require engagement of the scientific communities associated with IODP and the International Continental Scientific Drilling Program (ICDP).

3.3 Testing geodynamic models for subduction initiation, mega-thrust development, and deep biosphere development in the Puysegur Trench, south of New Zealand

The Puysegur incipient subduction zone south of New Zealand is an ideal location to constrain key geodynamic unknowns. Precise plate tectonic constraints along with a high level of seismicity reveal the transition of strike-slip motion along the Macquarie Ridge in the south to a clear Benioff zone and active subduction beneath southwestern South Island of New Zealand, in the north. It is likely that the Puysegur subduction zone is currently transitioning from a forced to a self-sustaining state. IODP drilling around Puysegur will allow testing and refinement of three topics fundamental to the IODP science plan 2013–2023: (1) the forces associated with subduction initiation, (2) the origin of subseafloor communities in the deep biosphere, and (3) the development of fault properties in a mega-thrust environment. Site survey data at Puysegur will be acquired with the R/V *Marcus Langseth* during February to March 2018 through the South Island Subduction Initiation Experiment (SISIE). Numerous associated paleoceanographic objectives will be addressed by drilling in this region, including a record of terrestrial runoff from New Zealand as the convergent plate boundary evolved, and records of sub-Antarctic sea surface conditions and paleoproductivity.

3.4 Stress state in the upper oceanic crust in a region of great intraplate earthquakes off Sumatra

The world's largest known intraplate earthquakes have occurred in the subducting Indian Plate offshore Sumatra, and have raised many questions about the genesis of such events. IODP Expedition 362 had two prospective sites approved for drilling (SUMA-22A and SUMA-23A) located 10–20 km to the north and south of the epicenter of one of these major intraplate earthquakes. Although approved for drilling, the sites were not drilled during Expedition 362 due to time constraints. However, these sites provide a unique opportunity to investigate the stress state in the region of these great intraplate earthquakes, and also to advance understanding of the sedimentary sequence entering the Sumatra subduction zone farther north, thereby building on the goals of Expedition 362. Depending on the scope, either an APL or a full proposal is planned to follow up on Expedition 362 objectives, and to investigate the state of stress state in upper oceanic crust near these highly seismogenic fracture zones.

4 New Zealand region: subduction inputs on Hikurangi Plateau, Hikurangi margin episodic fluid flow, Canterbury Basin fresh water, plus eruptive processes on Kermadec Ridge

4.1 Hikurangi subduction inputs

The Hikurangi margin of New Zealand is arguably one of the best locales on the planet to resolve controls on subduction megathrust slip behavior due to the strong along-strike variations in subduction interface slip behavior. The nature of the material entering the subduction zone on the subducting Pacific Plate likely exerts a strong control on these along-strike variations in slip behavior. This proposal will acquire cores and logs sampling the incoming sedimentary section and underlying Hikurangi Plateau at several sites along the Hikurangi Plateau (from north to south). These sites will illuminate along-strike variations in the sedimentary section and underlying Hikurangi Plateau, and how these variations in lithology and fluid content may influence locked versus creeping behavior at subduction megathrusts. It will target portions of the plateau where the sedimentary cover is less than several hundred meters, well east of the deformation front, to avoid thick trench-fill sections near the Hikurangi Trough. We will also target expanded sections of the portions of incoming stratigraphy that correlate with where the plate boundary décollement is forming.

4.2 Episodic fluid flow driven by slow slip and its impact on gas hydrate systems on the Hikurangi margin

Bottom simulating reflectors (BSRs) observed at the Hikurangi subduction margin and their relationship to geothermal heat flow changes suggest that regional gas hydrate systems may be strongly influenced by episodic fluid flow processes. These processes may be driven by large strain transients that occur during episodic slow slip events. This proposal seeks to install subseafloor observatories to monitor pore pressure and temperature changes throughout the slow slip cycle. Genius plugs with osmotic samplers could undertake time-series sampling of fluids to evaluate changes in geochemistry with time. These observatories will enable evaluation of the impact of fluid pulsing on gas hydrate systems, and also quantify the degree of overpressure that builds up beneath hydrate systems during and between fluid pulsing, potentially driven by slow slip events. The latter could also play a role in submarine slope stability processes. Installation of a denser network of simple observatories will also enable more detailed spatiotemporal investigation of the distribution of offshore slow slip events, allowing many questions about shallow slow slip distribution and its impact on hydrogeology in the upper plate to be addressed.

4.3 Offshore freshwater resources in the Canterbury Basin

Results from IODP Expedition 317 in the Canterbury Basin showed a freshening signature at ∼ 50 m depth at Site U1353, while nearby Site U1354 showed near-seawater salinity. This transition from a freshwater-charged zone to a non-freshwater zone makes an interesting and well characterized target to investigate the dynamics of, and interactions between, freshwater and seawater subseafloor hydrological systems. Abundant regional site survey data exist in this area, including a recent voyage that acquired seismic and controlled source electromagnetic data, to allow investigation of the freshwater system beneath the offshore Canterbury Basin. A future drilling proposal will include active pumping tests and potentially an observatory component to look at transients in these systems. Such an effort should also be of great interest to the biological community as the communities of freshwater and saline systems will be very different. Evaluating the communities in the transition between these systems should provide insights into microbiology and nutrient availability.

4.4 Eruptive processes and transport in submarine volcanic environments along the Kermadec Ridge

Marine volcanic eruptive processes and underwater transport/deposition of volcanic material are poorly understood. In particular, the transport and depositional processes during submarine eruptions, and the behavior of pyroclastic flows as they transition from onshore to offshore environments is understudied. In some historical cases (such as the Krakatoa eruption), large tsunami have resulted from these processes, so understanding the underlying mechanisms of eruption-fed volcaniclastic transport into and under water also has important geohazard implications. Recent drilling in the Izu–Bonin–Mariana arc system uncovered 20–100 m thick eruption-fed units, but drilling on the flanks of submarine volcanoes is more suited to fully investigate these processes. The Kermadec Arc is an attractive location for such an effort, because (a) a number of submarine volcanoes have always been submarine and also have produced eruptions with significant volume, and (b) Macauley Island is an excellent locale to investigate pyroclastic transport and depositional processes into the sea, where arcuate sediment waves are observed on the order of 100 m high and 1 km long.

Key questions include (1) what are the physics and processes behind submarine and coastal volcanic eruptions and subsequent deposition of their products, and (2) are the eruption products emplaced all at once, or do they occur in multiple episodes?

5 Conjugate margins and climate

5.1 Did CO_2 from geologic sources contribute to glacial–interglacial pCO_2 variability, and cause the formation of seafloor pockmarks on the Chatham Rise, New Zealand?

After three decades of scientific effort there is no definitive answer to the question "What Earth system processes were responsible for the systematic variations in atmospheric CO_2 during each glacial cycle of the late Pleistocene?" Our proposal seeks to investigate and test the hypothesis that geologic reservoirs act as capacitors, storing large volumes of CO_2 in marine sediments during glaciations and then leaking carbon to the ocean and atmosphere during glacial terminations. Recent discoveries have identified accumulations of both liquid and hydrate ($\sim$ solid) CO_2 in marine sediments at a variety of tectonic settings. These liquid and hydrate CO_2 reservoirs can undergo phase changes as temperature and pressure changes during glacial–interglacial cycles, affecting the storage and leakage of carbon to the overlying ocean. Evidence supporting this hypothesis includes large $\Delta^{14}C$ excursions in marine carbonates from the last glacial–interglacial transition that point to release of large quantities of ^{14}C-dead carbon to the ocean. To date, the largest $\Delta^{14}C$ excursions have been documented in the South Pacific on Chatham Rise and from the Galapagos margin. On Chatham Rise the $\Delta^{14}C$ excursions coincided with the formation of large pockmarks. The pockmarks extend over an area of $> 20\,000\,km^2$ and have been observed in seismic profiles in association with previous glacial terminations. The close temporal relationship between the $\Delta^{14}C$ excursions and the formation of pockmarks points to a causal relationship whereby CO_2 released from geologic reservoirs on Chatham Rise during the glacial–interglacial transition produced the pockmarks. The proposal sets forth a plan to investigate and test this hypothesis by obtaining and then studying sediment records from Chatham Rise that span each of the glacial cycles of the late Pleistocene.

5.2 Southeastern Chatham Rise margin: tectonics, dynamics, and paleoceanography

The southeastern continental margin of Chatham Rise is conjugate to the Amundsen Sea margin of West Antarctica. Deep crustal seismic, gravity, and magnetic data coupled with dredged samples from seamounts reveal a complex transition from continental to oceanic crust on both conjugate margin segments. In particular, the southeastern Chatham Terrace is underlain by a broad zone of thinned and fragmented transitional crust, presumably containing continental blocks separated by zones of oceanic crust. The nature of this type of transitional crust and the processes of its generation during Cretaceous rifting and breakup is poorly understood. The southern Chatham Rise is an ideal location to investigate crustal fragmentation during continental breakup by drilling into the different crustal zones, and could be combined with drilling into well-imaged sediment drifts to address hypotheses related to the development and evolution of southwestern Pacific Ocean circulation (e.g., Deep Western Boundary Current (DWBC) and ACC) during the Cenozoic.

5.3 Totten Glacier Cenozoic ice sheet evolution and sensitivity to past warming

Vulnerability of the East Antarctic Ice Sheet (EAIS) to climate change is uncertain. The low-lying, glacially sculpted Aurora Subglacial Basin (ASB; $\sim$ 3–5 m sea-level-equivalent ice) is a major marine-based East Antarctic catchment that drains ice from the Gamburtsev Mountains to the Sabrina Coast. The catchment consists of several overdeepened basins and hosts an active subglacial hydrological system, suggesting that regional ice may be susceptible to climate variability, particularly during warm climate intervals. New sediment records from the Sabrina Coast continental shelf will enable us to test fundamental hypotheses related to the existence of warm high southern latitude climates during the late Mesozoic and early Cenozoic, and evolution of the EAIS in the ASB from the Paleogene to the last deglaciation. The stratigraphic sequence also records variable meltwater influence, potentially critical for understanding catchment ice dynamics. Shelf records, though inherently discontinuous, offer advantages over deep-sea records, including the following: (1) direct records of ice margin fluctuations (e.g., lithologic changes, glacial erosion surfaces) and continental conditions (e.g., vegetation, temperature, hydrology), (2) shallow access to older strata due to tilting and glacial erosion of overlying strata, and (3) high sedimentation rates and shallow water depths, which favor carbonate macro- and microfossil (e.g., foraminifera, bivalves) preservation. Drilling the Sabrina Coast shelf will be technologically challenging. Proposed Sabrina Coast sites are located within a small polynya, which enhances ice risks and requires a mission specific platform. Drilling from a stable seabed drill or using ANDRILL-style riser drilling technology from an icebreaker will maximize recovery. This accessible archive of past Antarctic climate and ice sheet history will provide data to improve ice sheet and climate model boundary conditions and outputs. This type of data-model integration is required to better understand the response of Antarctica's ice sheets to continued anthropogenic warming.

5.4 Sabrina Coast slope deposits

This project aims to obtain high-latitude paleoclimate records from the Miocene to Pleistocene of ice sheet and ocean interactions at the East Antarctic margin to understand the history of Totten Glacier mobility and melting. It will obtain more continuous records of the oceanic drivers and responses to East Antarctic Ice Sheet variability than drilling on the continental shelf. It will also seek to obtain pre-Miocene records during past greenhouse climates, and correlation to continental shelf records in the Totten Glacier region in the proposal above (Sect. 5.3). Extensive seismic lines exist across the area with more than 28 crossing lines for selection of many potential drill sites. Turbidite overbank deposits are proposed as targets, as these were demonstrated during IODP Expedition 318 (Wilkes Land margin of East Antarctica) to provide high-resolution continuous archives of glacially-influenced sedimentation. Critically, such archives have proven valuable in identifying ice-sheet retreat events and characterizing these in the context of associated oceanographic change. Experience from an R/V *Investigator* voyage during January to March 2017 pointed to favorable weather conditions for coring in this area using standard *JOIDES Resolution* riserless drilling.

5.5 Southeastern Indian Ocean deep circulation and sediment drift history, basement depth, and mantle chemistry anomalies

The Southern Ocean encircles a highly dynamic glaciated Antarctic margin, and accommodates the amalgamation of several major water masses. Changes in the vigor of this top-to-bottom current would have significant implications for the exchange of heat between the Pacific, Indian, and Atlantic ocean basins, and may have consequences for the ventilation and primary productivity of the Southern Ocean. Contourite drifts are rapidly-deposited signatures of bottom current activity, and provide high-resolution records of paleoceanographic change. There are several lines of evidence suggesting that the Southeast Indian Ridge (SEIR) is covered extensively by a succession of Pleistocene to Pliocene-aged drifts. Long-term sedimentation rates exceed 5.5 cm kyr^{-1}, and focusing factors suggest extensive sediment winnowing by lateral advection of bottom currents. Furthermore, drilling results from Deep Sea Drilling Project (DSDP) Site 265 indicate "extremely high" sedimentation rates in the Quaternary. Recent ocean circulation numerical modeling also supports the accumulation of thick sediment drifts on the SEIR. The SEIR lies far from any terrigenous sources that could mask or otherwise contaminate any signals of bottom current intensity manifested within these sediment drifts. It is straightforward to combine the climate goals of such a proposal with petrological sampling of the Australian–Antarctic Discordance (AAD) and the eastern SEIR, aimed at testing alternative hypotheses about the origin of geochemical and depth anomalies along the SEIR (westward plume/asthenospheric flow along eastern SEIR towards the AAD versus mid-ocean ridge migration over an ancient slab burial ground). The two issues are connected in that anomalously elevated ridge segments act as potential obstacles along which contourites are deposited, while anomalously deep troughs and segments of the ridge may allow deep water to pass from one ridge flank to the other.

5.6 The Indian Ocean dipole and monsoon

The recovery of a sequence of Miocene to recent sediments from the eastern equatorial Indian Ocean will help resolve the history of the Indian Ocean dipole (IOD) on annual to tectonic timescales. The objectives of the drilling are to understand the following: (1) the evolution of sea surface temperatures (SSTs) in the eastern Indian Ocean since the Miocene, (2) the long-term relationship between eastern Indian Ocean SSTs and strengthening/weakening of the Indian monsoon, (3) the response of eastern Indian Ocean SSTs/IOD to atmospheric CO_2 forcing, and (4) the influence of a constricted Indonesian Throughflow (ITF) gateway at ∼ 3–4 Ma on the IOD. We propose drilling a latitudinal transect at ∼ 5° S (∼ 90–110° E) to obtain longer timescale records as old as early Miocene, in order to understand the evolution of SSTs and the effect of ITF gateway closure on IOD. Furthermore, we propose drilling off the west coast of Sumatra, which will be helpful in obtaining high-resolution sediment cores to understand variations in the IOD at decadal to centennial timescales. This proposal will be amalgamated with an earlier plan, which aimed to understand Nicobar fan evolution, monsoon intensity and Himalayan uplift, and the stress state in oceanic crust and relationship to seismicity.

5.7 Future IODP drilling in northern Zealandia/Lord Howe Rise

Northern Zealandia and the Lord Howe Rise were drilled during IODP Expedition 371 using *JOIDES Resolution* from July to September 2017, and is planned to be drilled during a SEP/CIB-approved D/V *Chikyu* expedition that, subject to funding, is scheduled for the second half of 2020 (Complementary Project Proposal 871-CPP). New opportunities for drilling in northern Zealandia will undoubtedly emerge from the core and data collected during Expedition 371, which is investigating Eocene Tonga-Kermadec subduction initiation and evaluating whether a period of high-amplitude long-wavelength compression led to initiation of subduction or determine if alternative geodynamic models were involved. Moreover, Paleogene and Neogene sediments recovered during Expedition 371 are also constraining paleoceanographic changes caused by subduction initiation as well as tropical and polar climatic teleconnections and the transition from greenhouse to icehouse climate states. In the case of Proposal 871-CPP for deep riser drilling to investigate Lord Howe

Rise crustal ribbon development, ocean biogeochemical cycles at high southern latitudes from the Cretaceous onwards, and the limits of life beneath the ocean floor, several proposed alternate sites may be suitable for riserless drilling using *JOIDES Resolution*.

New site survey data obtained in support of these recent and planned expeditions provide modern seismic coverage of the entire width of northern Zealandia from the Norfolk Ridge to the Tasman Sea oceanic basin. These data undoubtedly reveal a large number of additional drill sites, many of which have not yet been considered in detail. Another possible long-term objective in the region is to target seamounts and submerged plateaus within and to the north of northern Zealandia where drilling could address important geodynamic questions surrounding changes in Pacific Plate motion, and the connections among deep mantle plumes and large igneous provinces. It was agreed at the workshop that future plans for IODP drilling in northern Zealandia should be revisited in mid-2018 after results from Expedition 371 begin to emerge and the status of funding and logistics for Proposal 871-CPP is clearer.

5.8 Completing the Australian–Antarctic transect

The Australo–Antarctic rift system affords an opportunity to document lithosphere thinning history during continental breakup, and to understand the transition between rift and oceanic crust formation. The peridotite ridge in this region, representing the boundary between continental and oceanic crust, has risen high enough to be reached with riserless drilling. A second aim is to understand the timing, nature, and consequences of post-rift subsidence of the outer continental shelf of both the Australian and Antarctic margins. It is expected that post-rift subsidence was minimal, because continental migration was compensated for by formation of oceanic crust. Both margins should be completely independent in terms of subsidence history as soon as oceanic crust formation commences, but evidence from IODP Expedition 318 (Wilkes Land) suggests that the outer continental shelf of the Antarctic margin collapsed long after oceanic crust started forming in the rift system. Moreover, and surprisingly, seismic profiles along the conjugate Australian and Antarctic margins show considerable symmetry. However, on the Australian side, we lack recovered sedimentary records that allow dating of the sediments from the seaward limit of the continental margin. The region also has fundamental climate questions to address, including the deep-sea expression of Eocene–Oligocene glaciation and circum-Antarctic erosion, and the history of the development of the ACC and spatial migration of Southern Ocean frontal systems. It was proposed to develop a plan to drill a transect which connects the Otway–Ceduna basins (Australian margin) and the Antarctic margin.

6 Biosphere

6.1 Reflux brines: linking continental shelf hydrogeology to subseafloor microbiology

The role of mass transport in continental margin environments has historically been underappreciated. Recent oceanographic tracer studies indicate that discharge of saline groundwater from passive continental margins occurs at rates equal to, or exceeding, river discharge. This implies large-scale migration of saline groundwater through continental shelf sediments and is consistent with decades of research in carbonate diagenesis, where the importance of groundwater mass transport has long been recognized. Sea-level pumped reflux brines, formed by evaporation of seawater on the exposed shelf during sea-level minima, should be common in subtropical passive margin sequences, and may provide the missing mechanism to explain the large-scale dolomitization and mineralization processes observed throughout Earth's history. These shelf-scale hydrological systems may also support abundant deep microbial life on the upper shelf slope.

Results from ODP Leg 182 show that Great Australian Bight (GAB) likely contains an actively discharging reflux brine system. Two transects across the outer GAB margin were proposed to assess coupled groundwater flow, geochemical reactions and microbial metabolic processes. Results from ODP Leg 182 suggest that the brine-supported microbial ecosystem in the GAB thrives under hyper-alkaline and hyper-sulfidic conditions, which are profoundly distinct from most other known deep biosphere environments. The tantalizing possibility is that we will gain an unprecedented glimpse into the microbial and organic geochemical processes that are responsible for the formation of a large portion of the world's hydrocarbon resources, as well as determining the role of saline groundwater flow in carbonate diagenesis in continental margin environments.

6.2 The edge of the gyre: biological and oceanographic transitions from the South Pacific Gyre into the Southern Ocean through the Cenozoic

A transect of sites from the South Pacific Gyre into the Southern Ocean will record a north–south gradient of different biogeochemical and oceanographic regimes within oxic and suboxic sediments through the Cenozoic. Microbiological research will help to address questions honed from the results of IODP Expedition 329 to the South Pacific Gyre. One of its most southern sites (Site U1371) included a shift from pelagic clay sedimentation to siliceous accumulation at ~ 8 Ma, and the microbial communities between these two lithological units are unique. Drilling additional sites on the southernmost edge of the South Pacific Gyre that focus on acquiring these types of depositional and biogeochemical transitions will allow the examination of how microbial ecosystems are established and respond to changing environments. This region is critically underexplored in ocean drilling, and numerous paleoceanographic questions could also be addressed in this understudied region, although further work is required to develop specific hypotheses to test.

7 Consensus statement regarding the critical importance of site characterization data for IODP scientific drilling proposals

The 97 scientists from 12 different countries gathered at the 2017 Australasian IODP Workshop in Sydney, tasked with planning scientific ocean drilling expeditions in the eastern Indian, southern, and southwestern Pacific oceans, emphasize the critical importance of geoscientific site characterization to the future success of IODP and its successors. Site characterization data, most importantly seismic reflection data, are essential for the identification of suitable primary and alternate drill sites in every full drilling proposal submitted to the IODP science support office, and are subsequently carefully considered by the program's science evaluation panel (SEP) and the three facility boards.

Without this type of information, the scientific exploration of the deep subseafloor and our understanding of its role in tectonic, climatic, oceanographic, biological, and geochemical processes in the Earth system cannot advance. Providing suitably capable vessels for that purpose is essential for the advancement of scientific ocean drilling as it addresses ever-evolving global scientific questions, particularly in underexplored parts of the world ocean like the Australasian region.

Accordingly, we emphasize that blue water research vessels with the necessary seismic reflection systems should continue to be available to researchers in all IODP member countries under reasonable fiscal conditions, and with suitable advance (national and international) planning mechanisms.

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

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

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Scientific Drilling
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Workshop Reports

The Lake CHAd Deep DRILLing project (CHADRILL) – targeting $\sim$ 10 million years of environmental and climate change in Africa

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Abstract. At present, Lake Chad ($\sim 13^{\circ\prime}$ N, $\sim 14^{\circ}$ E) is a shallow freshwater lake located in the Sahel/Sahara region of central northern Africa. The lake is primarily fed by the Chari–Logone river system draining a $\sim 600\,000\,km^2$ watershed in tropical Africa. Discharge is strongly controlled by the annual passage of the intertropical convergence zone (ITCZ) and monsoon circulation leading to a peak in rainfall during boreal summer. During recent decades, a large number of studies have been carried out in the Lake Chad Basin (LCB). They have mostly focused on a patchwork of exposed lake sediments and outcrops once inhabited by early hominids. A dataset generated from a 673 m long geotechnical borehole drilled in 1973, along with outcrop and seismic reflection studies, reveal several hundred metres of Miocene–Pleistocene lacustrine deposits.

CHADRILL aims to recover a sedimentary core spanning the Miocene–Pleistocene sediment succession of Lake Chad through deep drilling. This record will provide significant insights into the modulation of orbitally forced changes in northern African hydroclimate under different climate boundary conditions such as high CO_2 and absence of Northern Hemisphere ice sheets. These investigations will also help unravel both the age and the origin of the lake and its current desert surrounding. The LCB is very rich in early hominid fossils (*Australopithecus bahrelghazali*; *Sahelanthropus tchadensis*) of Late Miocene age. Thus, retrieving a sediment core from this basin will provide the most continuous climatic and environmental record with which to compare hominid migrations across northern Africa and has major implications for understanding human evolution. Furthermore, due to its dramatic and episodically changing water levels and associated depositional modes, Lake Chad's sediments resemble maybe an analogue for lake systems that were once present on Mars. Consequently, the study of the subsurface biosphere contained in these sediments has the potential to shed light on microbial biodiversity present in this type of depositional environment.

We propose to drill a total of $\sim$ 1800 m of poorly to semi-consolidated lacustrine, fluvial, and eolian sediments down to bedrock at a single on-shore site close to the shoreline of present-day Lake Chad. We propose to locate our drilling operations on-shore close to the site where the geotechnical Bol borehole (13°28′ N, 14°44′ E) was drilled in 1973. This is for two main reasons: (1) nowhere else in the Chad Basin do we have such detailed information about the lithologies to be drilled; and (2) the Bol site is close to the depocentre of the Chad Basin and therefore likely to provide the stratigraphically most continuous sequence.

1 Introduction

Covering almost 8 % of the continent, the Lake Chad Basin (LCB) is the largest endhoreic drainage basin in Africa (2.5×10^6 km^2) and one of the largest intracratonic basins on Earth (Fig. 1). Formation of accommodation space started during the Cenozoic (Burke, 1976) with nearly continuous deposition of terrestrial/lacustrine sediments since ∼ 10 Myr (Lebatard et al., 2008; Schuster et al., 2009). Today's Lake Chad is a terminal and highly variable shallow freshwater lake (∼ 3 m deep, measured in 2012) with a strong S-to-N conductivity gradient (50 to 700 µS cm^{-1}; Bouchez et al., 2016). The annual invigoration of the northern African monsoon system and migration of the intertropical convergence zone (ITCZ) results in a short rainy season from June to October and a pronounced dry season for the rest of the year. During recent decades, the lake level varied by up to 4 m, with a highstand in the 1960s, a prolonged lowstand in the 1970s, and a recovery phase since the beginning of the 2000s, thus emphasizing that lake-level changes reflect regional changes in rainfall (Lebel and Abdou, 2009). The latter together with its location at the interface of the African tropics and subtropics make the LCB sediment record a promising target to trace back changes in moisture variability in northern Africa under very different climate boundary conditions. Reconstructing the region's moisture variability since the Miocene would provide a very detailed picture of the environmental response to climate states with high atmospheric greenhouse gas (GHG) concentrations and limited Northern Hemisphere ice-sheet extent. This includes fundamental insights into the strength of modulation of orbitally forced changes in monsoon intensity and the effect of changes in ITCZ shifts/expansion under climate conditions common to the pre-Pleistocene. In addition, providing a glimpse into periods when both GHG concentrations and orbital parameters were similar to today will allow us to better constrain the impact of possible near-future climate states on the regional environment and societies. Such a study is timely given the enormous importance of today's lake as a freshwater and food source for ∼ 47 million people (Lemoalle and Magrin, 2014) and the region's recent history of conflict.

With the discovery of several hominin remains associated with a rich fauna (Brunet et al., 1995, 2002), the LCB has been recognized as one of the cradles of humanity. Hominin remains, from the LCB and elsewhere in northern Africa (Hublin et al., 2017), demonstrate that the emergence of humans was not restricted to the East African Rift region. These discoveries not only raise important questions about the origin of humankind, but also strengthen the debate concerning the environmental triggers, such as precipitation variability, which may have impacted human evolution (Blome et al., 2012; Shultz and Maslin, 2013). A spatially better resolved picture of climate forced changes in environmental conditions and habitability in regions outside the rift valley is therefore required to elucidate their role in the evolution of modern humans. Until recently, it was considered that the Sahara was a natural obstacle to human migration, with the Nile as the only optimal corridor allowing northwards passage from the African tropics. Nevertheless, some studies show that the Sahara was probably not a continuous barrier and that both animals and humans may have populated the region during past humid phases known as Green Sahara Episodes (Larrasoaña et al., 2013). Other evidence even suggests a potential link between the Mediterranean Sea and the LCB via the ancient Esohabi River system in Libya, emphasizing the central Sahara as an alternative potential route for hominin dispersal (Griffin, 2006; Osborne et al., 2008; Drake et al., 2010).

The role of climate in the evolution and dispersal of hominid ancestors was probably amplified during the Tortonian (11.6–7.2 Myr), when shrinkage of the Tethys is thought to have been the main driver for the increasing aridity of Africa and formation of the Sahara (Zhang et al., 2014). As a consequence, the sensitivity of the African monsoon system to orbital forcing increased, making it the predominant driver for the cyclic expansion and contraction of the Sahara (Tuenter et al., 2003). However, there are some outstanding questions that are still debated, such as the timing of the formation of the Sahara. Both marine (Atlantic Ocean, Ruddiman and Janecek, 1989; Mediterranean Sea, Rose et al., 2016) and continental records (Chad Basin; Schuster et al., 2006) suggest a Late Miocene timing (close to the end of the Tortonian at 7 Myr), whereas other authors suggest that evidence prior to the onset of Northern Hemisphere glaciations at ∼ 3 Ma (Swezey, 1999) is insufficient to support such a proposition.

Previous studies propose that the LCB was the source of the Esohabi River, a paleoriver system flowing northward from the southern Libyan desert down to the Mediterranean Sea during the Late Miocene (Griffin, 2006; Ghoneim et al., 2012). Although this river no longer flows today, climate models suggest that enhanced monsoonal rains in northern Africa fed it, and that it was roughly equivalent in size and magnitude to the present-day Nile (Gladstone et al., 2007). The freshwater flux influenced not only the immediate envi-

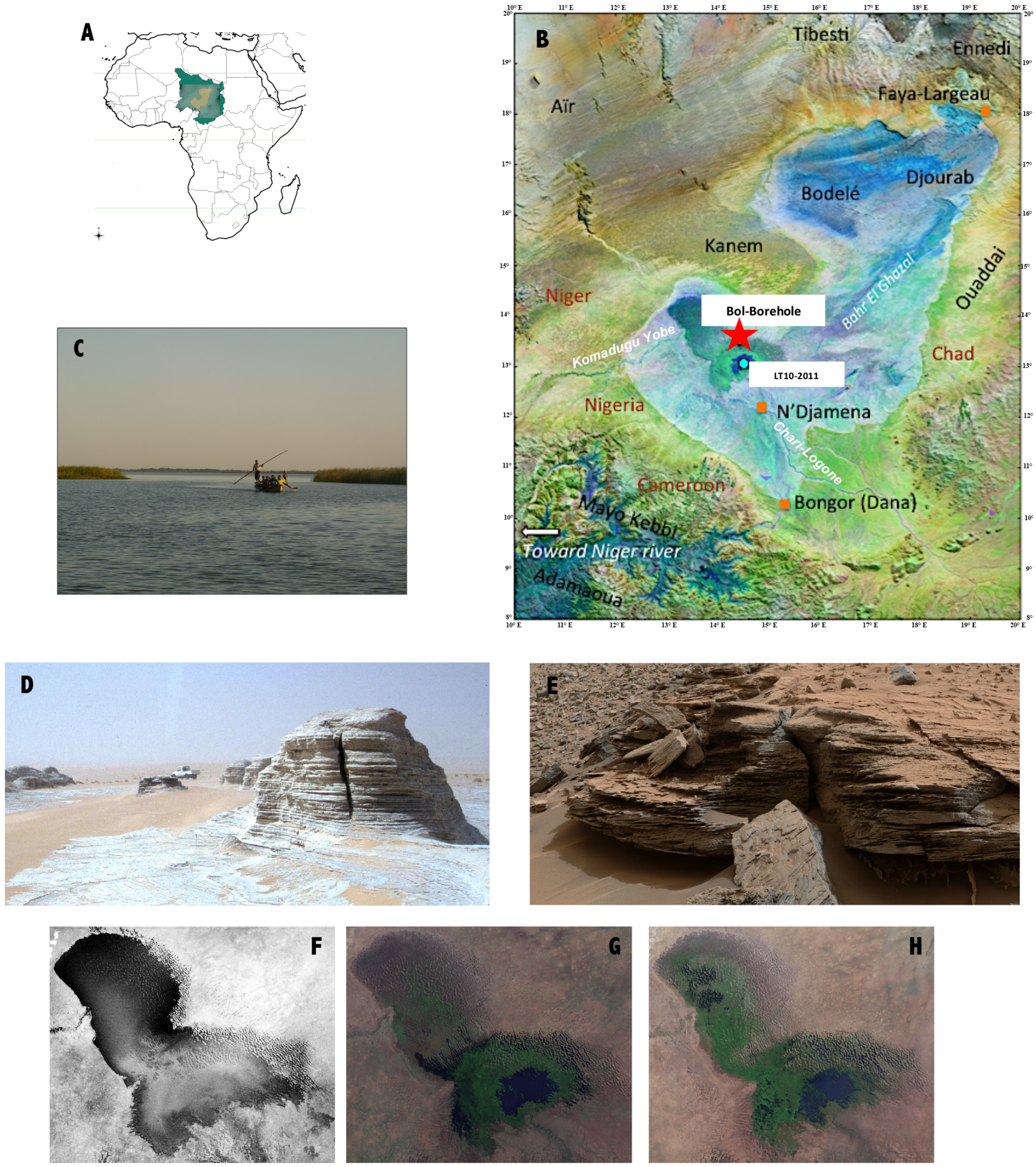

Figure 1. **(a)** Political map of Africa showing the Lake Chad hydrological basin. **(b)** SRTM map of the region surrounding Lake Chad. The shaded blue area marks the extension of the mega Lake Chad during the Holocene with an area of 34×10^4 km^2. The principal populated towns are marked by red squares. The blue circle indicates the location of the previous core (LT10-2011) and the red star the borehole at Bol. **(c)** Picture of fishermen from Lake Chad. **(d)** Diatomite-dominated sequences deposited during previous transgressive episodes of Lake Chad currently outcropping in the Djourab region (see Fig. 1b for the location). The sediments date back to Holocene diatomites (Schuster et al., 2009). **(e)** Sediments of Mars (Rover pictures). Landsat images show the extension of the lake in 1963 **(f)**, 1987 **(g)**, and 2003 **(h)**.

ronmental conditions of the Mediterranean region, but also may have been a driver of Mediterranean–Atlantic exchange and hence North Atlantic thermohaline circulation (Bryden and Kinder, 1991). Consequently, the record preserved in Lake Chad has implications for a climate system that spans half the globe, and is a critical transfer mechanism for water, salt, heat and nutrients from the equatorial to polar latitudes.

Our vision to obtain long sedimentary records from the LCB will also assess the dynamics of intracontinental basins through time and space. Sediments outcropping around Lake Chad show intriguing similarities to those discovered by the ongoing Curiosity Mars mission (Fig. 1e). This striking similarity makes the LCB a promising analogue for similar freshwater systems that were once present on Mars. Studying the subsurface biosphere in combination with in-depth investigation of associated diagenetic processes has the potential to provide valuable insights into the present query of early life on Earth and other planets. The strategy that NASA

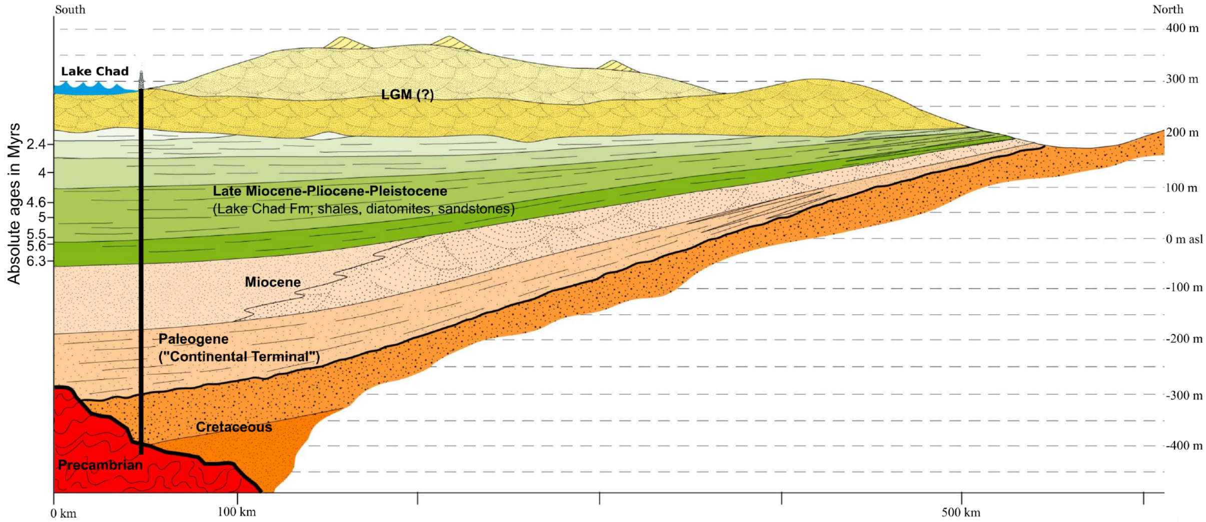

Figure 2. Synthetic and interpretative N–S geological transect across the Chad Basin showing the lateral extent and thickness of palaeo-Lake Chad beds (modified from Moussa, 2010).

will use during the already scheduled missions looking for signs of extra-terrestrial life will put special emphasis on microbially influenced sedimentary structures. These kinds of structures can be potentially recognized in the Lake Chad cores and compared to those identified with the new generation of instruments that will be sent to Mars in 2020. Among them a Close-UP Imager called CLUPI has been developed at the Space Exploration Institute (Space-X) of Neuchâtel, Switzerland, and will look at the subsurface of Mars through coring (Tomaso Bontognali, personal communication, 2017).

2 Workshop structure and outcomes

In view of the enormous opportunity for a scientific drilling project to investigate the sedimentary record of the LCB, an ICDP-sponsored workshop was organized in Aix-en-Provence from 21 to 23 September 2016. Overall, 51 scientists and government officials from 11 countries (Belgium, Cameroon, Chad, France, Germany, Israel, Nigeria, Spain, Switzerland, UK and USA) participated in the discussion that framed the scientific objectives as well as challenges associated with the technical and logistical aspects of an ICDP drilling project in the LCB.

The workshop commenced with a full day of presentations on the key science themes, results from ongoing and previous research in the LCB, as well as broader overview talks on the northern African climate evolution since the Miocene and the associated responses of the biosphere. Participants paid particular attention to the presentations on sedimentological, chronological, and paleoenvironmental datasets obtained from a 673 m deep geotechnical borehole that reached bedrock at an on-shore site close to the city of Bol on the north-eastern shore of Lake Chad (Figs. 1 and 2), considered the depocentre of the LCB (Burke, 1976). Datasets obtained from core cuttings and drill logs emphasize the presence of ∼600 m thick Miocene to Early Pleistocene deposits composed of fine-grained terrestrial deposits below a ∼70 m thick succession of Late Pleistocene dune sands (Fig. 3). Deposits in the succession between ∼70 and 300 m, where core cuttings are available, comprise fine-grained muds, diatomaceous oozes, and diatomites with structures ranging from massive to finely laminated (Moussa et al., 2016). Authigenic ^{10}Be burial dating (Lebatard et al., 2010) along with biostratigraphic constraints (Novello et al., 2015) place this succession between 6.3 Myr (∼300 m depth) and 2.4 Myr (∼90 m depth). These deposits thus represent nearly continuous sedimentation in a lacustrine setting similar to today's Lake Chad. Chronological as well as detailed lithological information is not available from the lower succession (∼300–673 m) due to the lack of core cuttings. However, drill logs from the lower succession suggest that fine-grained lacustrine muds and diatomaceous oozes, though more often intercalated with more extensive sand-sized deposits, prevail (Moussa et al., 2016).

Other stratigraphic information from exploration boreholes in Chad and Nigeria indicates either more condensed lacustrine successions or depositional environments with a stronger influence of deltaic processes (especially to the south). Outcrop studies undertaken in the northern Chad Basin emphasize the stronger influence of deflation at potential drill sites. The deep structure of the Chad Basin (i.e. location of the basement and thickness of sedimentary infill), synthesized in Servant-Vildary (1973), Burke (1976) and Servant (1983), is, notably, based on the geophysical characterization (e.g. gravimetry, isostacy) produced by Louis (1970) as well as on available data from exploration boreholes. To-

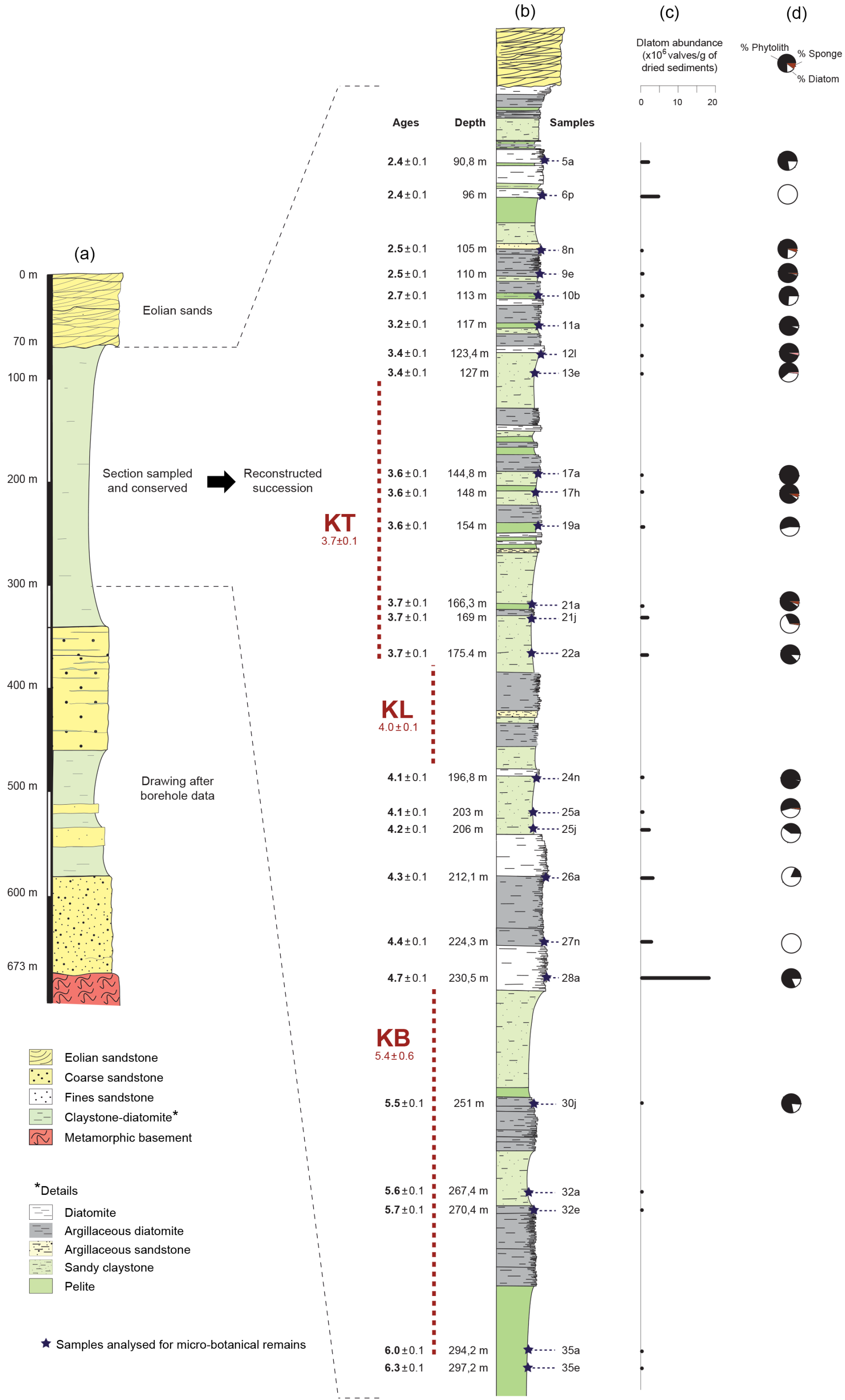

Figure 3. Sedimentology of the Bol borehole, chronology and stratigraphical positions of the 25 samples studied in detail (from Novello et al., 2015) with **(a)** general lithological succession of the whole core and ^{10}Be chronology (the position of the Mio-Pliocene fossil sites from Djourab is located in parallel to the chronology of the borehole), **(b)** a detailed sequence reconstructed from preserved cuttings, **(c)** diatom concentration in the studied samples (number of valves/g dry sediments), and **(d)** quantification of phytoliths, diatoms and sponge spicules recovered in the silicified assemblages (Novello et al., 2015; Moussa et al., 2016).

gether, these data suggest that the thickest accumulation of sediment occurred in the vicinity of present-day Lake Chad. There, the infill of the basin is documented by several shallow to deep boreholes (Roche, 1973; Servant, 1983). Among the seven deep boreholes published by Servant (1983; see Fig. 13), the one done in Bol shows the thickest sedimentary succession.

Based on these data and recent studies on core cuttings from the Bol exploration borehole (Novello et al., 2015; Moussa et al., 2016), the participants targeted the Bol site as the most promising location for obtaining a long and more continuous record from the LCB. This decision, based on the scientific value of the site, was strongly supported by Chadian government officials, who emphasized the site's accessibility and local infrastructure suitable for hosting a scientific drilling operation.

The second day was dedicated to topical break-out group discussions targeting the main thematic and disciplinary aspects and aimed at developing detailed scientific objectives and strategies capable of reaching major research goals. In addition, discussions elaborated the scientific working programme, and identified synergies between different groups, proxies, and analytic methodologies to be applied to reach the research goals. During the final day's morning session, funding strategies were developed, responsibilities were allotted, and a timeline for reaching milestones towards the realization of a comprehensive scientific drilling programme in the LCB was established. We also intensively discussed security in the field, which constitutes one of the greatest challenges for CHADRILL drilling operations. Because of our strong support by the Chadian authorities, we will be able to determine the best window for planning and executing the CHADRILL drilling operation. Last, but not least, one important aspect of the CHADRILL project is capacity building and the societal benefits of the proposed work. We dedicated a plan for involving students for Chad and the countries bordering the lake in our programme. Moreover, the first avenue for education and outreach is communicating knowledge to government authorities and other stakeholders (public and private). Lake Chad is central to the economic development of the region. This drilling project will contribute to a better understanding of water-resource availability, which is essential for long-term economic development and stability in the region.

As a result of the break-out group discussions, the workshop participants formulated what would be the major scientific objectives of a CHADRILL scientific drilling programme. In summary, long sediment drill cores from the LCB will allow us to:

- document the mechanisms by which orbital forcing, continental ice-sheet volume/extent, and changing atmospheric CO_2 concentration influence northern African climate and environment;
- identify the climatic context that shaped environmental conditions favourable for human dispersal into northern Africa;
- identify the depositional context of the early stages of basin formation and explore the possible link to the Mediterranean Sea;
- provide valuable information on the origin of the Sahara and the evolution of ecological diversity across multiple vegetation zones;
- explore the limit of the deep biosphere and the factors controlling the abundance and activity of microbes in the sediments;
- and put recent hydrological changes in Lake Chad into the context of its long-term evolution with a view to evaluating its sustainability and that of the societies it supports.

In order to meet these objectives, drilling will be performed at a location close to the site where the geotechnical borehole was drilled in the 1970s. The primary target of CHADRILL operations would be to recover a complete succession of the lacustrine deposits present between ~ 70 and 300 m depth. Secondary targets will focus on the recovery of sediments from the lower (~ 300–670 m depth) succession of more heterogeneous lacustrine deposits, and upper (0–70 m depth) dune sands. The envisaged CHADRILL research programme would thus complement previously accomplished and upcoming ICDP co-sponsored lake-drilling projects on the African continent and help to complete the vision of a dense global network of continental paleoclimate records that elucidate how climatic change altered the environment on local to regional scales. A CHADRILL record would furthermore form an excellent tandem with the envisioned recovery of palaeoclimate records from Lake Tanganyika. Both records are proposed to extend timescales back to the Miocene, north and south of the Equator, thus offering unprecedented insight into the climatically and geodynamically driven ecosystem evolution of the continent.

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

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Scientific Drilling
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The Newberry Deep Drilling Project (NDDP) workshop

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Abstract. The important scientific questions that will form the basis of a full proposal to drill a deep well to the ductile–brittle transition zone ($T > 400\,°C$) at Newberry Volcano, central Oregon state, USA, were discussed during an International Continental Drilling Program (ICDP) sponsored workshop held at the Oregon State University-Cascades campus in Bend, Oregon, from 10 to 13 September 2017. Newberry Volcano is one of the largest geothermal heat reservoirs in the USA and has been extensively studied for the last 40 years. The Newberry Deep Drilling Project (NDDP) will be located at an idle geothermal exploration well, NWG 46-16, drilled in 2008, 3500 m deep and 340–374 °C at bottom, which will be deepened another 1000 to 1300 m to reach 500 °C. The workshop concluded by setting ambitious goals for the NDDP: (1) test the enhanced geothermal system (EGS) above the critical point of water, (2) collect samples of rocks within the brittle–ductile transition, (3) investigate volcanic hazards, (4) study magmatic geomechanics, (5) calibrate geophysical imaging techniques, and (6) test technology for drilling, well completion, and geophysical monitoring in a very high-temperature environment. Based on these recommendations, a full drilling proposal was submitted in January 2018 to the ICDP for deepening an existing well. The next steps will be to continue building a team with project, technology, and investment partners to make the NDDP a reality.

1 Introduction/workshop objectives

An International Continental Drilling Program (ICDP) sponsored workshop was held in Bend, Oregon, USA, from 10 to 13 September 2017 with the main goal of discussing the elements of a full proposal for drilling to the ductile/brittle transition zone ($T > 400\,°C$) at Newberry Volcano, central Oregon state, in the Cascades volcanic arc of the US Pacific Northwest (Fig. 1). During the 4-day workshop, which included a field trip to the Newberry Caldera and the geothermal test facility, the 55 participants from 11 countries explored several important scientific questions that would form the basis of a full drilling proposal. The full agenda and the list of participants can be found on the ICDP website (https://www.icdp-online.org/projects/world/north-and-central-america/newberry/, last access: 10 October 2018). The main research goals are related to heat and mass transfer in the crust from the point of view of natural hazards and geothermal energy: enhanced geothermal system (EGS supercritical and beyond-brittle), volcanic hazards, mechanisms of magmatic intrusions, geomechanics close to a magmatic system, calibration of geophysical imaging techniques and drilling in a high-temperature environment.

Drilling at Newberry will bring additional information to a very promising field of research initiated by the Deep Drilling project in Iceland with IDDP-1 on Krafla in 2009

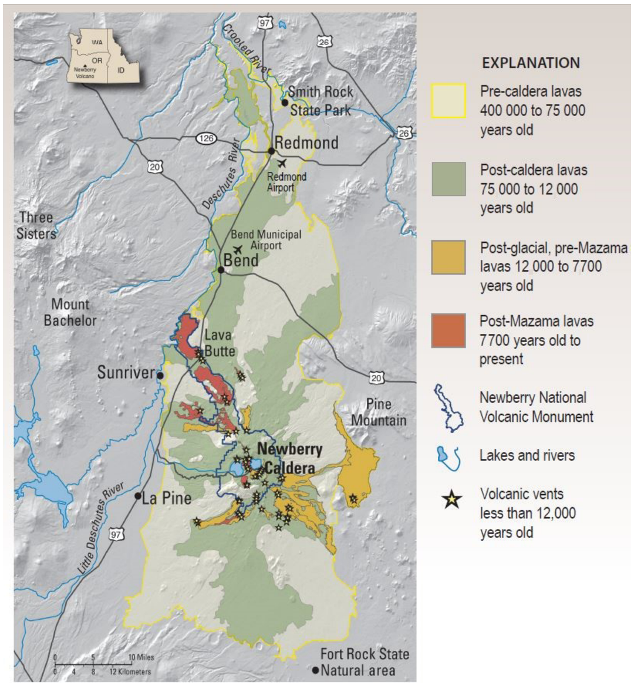

Figure 1. Lava flows and young volcanic vents at Newberry Volcano. The USGS continues to study and monitor the area (from Donnelly-Nolan et al., 2011). Figure 2 below shows the position of the NDDP target well.

(Friðleifsson et al., 2014a), followed by IDDP-2 on the Reykjanes ridge (Friðleifsson et al., 2014b) in 2016, DESCRAMBLE in Italy (Bertani et al., 2018) in 2017, in the future Krafla Magma Drilling Project (John Eichelberger, personal communication, 2017), and the future Japan Beyond-Brittle project (Asanuma et al., 2015; Muraoka et al., 2014). The main results and progress of these important projects were presented by their principal investigators during the workshop.

2 Newberry Volcano

2.1 Geology

Newberry Volcano is a broad shield volcano (Williams, 1935) that has been active for approximately the last 600 000 years (MacLeod et al., 1982; Jensen, 2006). The volcano constructed an elliptically shaped massif approximately 50 km by 30 km, and some lava flows reach more than 64 km to the north of the caldera (Fig. 1). Infrequent, widely distributed boulders with exotic lithologies interpreted to be glacial erratics (Donnelly-Nolan and Jensen, 2009) may indicate the presence of a glacier at the summit prior to the cataclysmic eruption at ∼ 75 ka that created the current caldera.

The more gently sloped lower flanks are composed of ash and lahar deposits, basaltic lava, cinder cones, and minor silicic domes. Several basalt flows sourced from the Northwest Rift located 100 km southwest of the proposed ICDP drill site are younger than 7000 years, the age of the regionally extensive Mazama ash from Crater Lake (McKay et al., 2009). The more steeply sloped upper flanks of the volcano are composed predominantly of overlapping silicic domes and subordinate basaltic rock. The central caldera formed ∼ 75 000 years ago is about 8 km by 5 km in extent, and is now a nested composite of craters and vents containing two lakes: Paulina Lake to the west at an elevation of 1930 m and East Lake to the east at an elevation of 1941 m. The Big Obsidian Flow represents the most recent eruption in the caldera, which occurred between 1.6 and 1.3 ka. The elevation of the rim of the caldera ranges from 2133 to 2408 m, except along the breached western side, where the elevation is 1929 m.

2.2 Geothermal

Newberry Volcano contains one of the largest geothermal heat reservoirs in the western United States, and has been extensively studied for the last 40 years (Bargar and Keith, 1999; Frone, 2015; Sammel et al., 1988; Swanberg et al., 1988). All the knowledge and experience collected make this an excellent choice for drilling a well that will reach high temperatures (>450 °C) at relatively shallow depths (< 5000 m). The large conductive thermal anomaly (320 °C at 3000 m depth) has already been well characterized by extensive drilling and geophysical surveys (Cladouhos et al., 2016; Mark-Moser et al., 2016). Four deep (more than 3000 m deep) boreholes completed in the geothermal lease area on the western flank of the volcano have shown that a natural hydrothermal system is not present outside the caldera, although geothermal hot springs do exist inside the large caldera to the east. Outgassing of magmatic CO_2 at one of the deep wells suggests some degree of connectivity exists between deeper magma bodies, possibly those mapped through seismic tomograms beneath the caldera, and the otherwise impermeable western flank geothermal leasehold area. Three large (20 000 m^2) geothermal pads exist on the geothermal leasehold and eight monitoring boreholes drilled up to 289 m deep have been used for sampling of shallow groundwater and for continuous seismic monitoring since 2012. In addition to the geothermal conditions appropriate for conventional and super-critical EGS, the prospect of geothermal energy research and development at the Newberry Deep Drilling Project (NDDP) site has the strong support of all the local communities eager for the economic boost that geothermal energy would bring to the area. That support has arisen through many years of public outreach and engagement during the Newberry EGS demonstration and monitoring projects (Cladouhos et al., 2012) that preceded the ICDP workshop at the OSU-Cascades campus in Bend.

A robust conceptual geologic model was developed in 2016 during phase 1 of the US DOE FORGE program (PNNL, 2016). A 3-D model, developed using the

EarthVision™ software environment, provides a unified framework which identifies the geological units, constrains their spatial extent, and characterizes properties of relevance to well deepening and geothermal exploration. In the conceptual model, the temperature profile is constrained by borehole equilibrium temperature measurements from deep wells, backed by thermal conductivity measurements of rock cores and cuttings. Additional constraints on porosity and permeability were inferred from seismic, 3-D gravity and 2-D and 3-D magnetotelluric (MT) models. Fluid content at the site is limited to a shallow aquifer or aquifers that extend to depths of 150 to 300 m below ground surface, beneath which increasing alteration of the volcanic minerals to clays, zeolites, and other moderate-temperature minerals decreases permeability substantially to form a thick low-permeability zone, as observed in cores, well logs, mud logs, and electrical resistivity values. Structural characteristics have been defined by decades of geologic studies, recent high-resolution lidar (light detection and ranging) mapping, seismic tomographic and waveform modeling, MT and gravity inversions, and by ground deformation monitoring. The stress regime has been evaluated by regional seismic focal mechanism studies, by interpretation of faults and volcanic features aligned along structural controls, borehole breakouts, and by simulations carried out during the US Department of Energy supported Newberry EGS Demonstration Project (Cladouhos et al., 2016). This conceptual geologic model and update of the site characterization inventory demonstrate that Newberry Volcano is one of the most extensively characterized EGS sites in the USA, making it an ideal location for implementation of an ICDP drilling project.

AltaRock Energy holds over 9000 acres of the Bureau of Land Management (BLM) geothermal leases on the northwestern flank of Newberry (Fig. 2). The leased area includes two deep geothermal wells, three large drilling pads, two water wells, and connecting roads. AltaRock Energy has permits in hand to drill an additional geothermal well and to carry out extensive microseismic monitoring. Oregon State University has permits in hand to carry out large array MT, controlled-source electromagnetic, gravimetric and ground deformation monitoring. Workovers or deepening of either existing well can be approved through a sundry notice to the BLM.

The two geothermal wells within the geothermal lease, NWG 46-16 and NWG 55-29 on pads 16 and 29 (Fig. 2), have conductive thermal gradients of 110 °C km^{-1} starting at 300 m and continuing to TD, with bottom hole temperatures of over 310 °C at 3000 m; thus, 500 °C can be expected at depths below 5000 m in either well. Unlike wells drilled in many conventional, fracture-dominated geothermal resources, these wells were drilled with full returns; that is, all cuttings were returned to the surface for analysis. Thus, we expect that successfully getting samples out of a deeper hole will be a high probability.

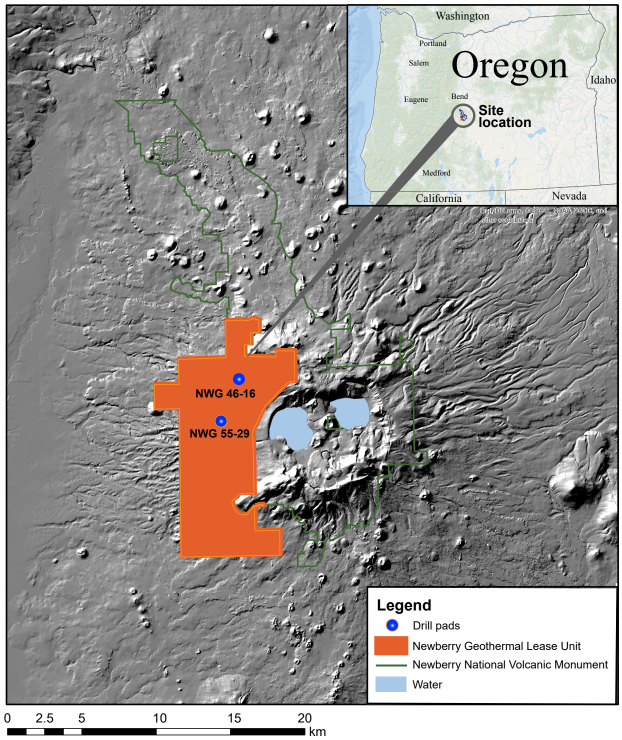

Figure 2. Location of the proposed NDDP well at NWG 46-16. Well NWG 55-29, the Newberry National Volcanic Monument and the geothermal lease are also indicated.

3 Critical scientific and technical questions and strategies to address them through the NDDP

3.1 EGS (supercritical and beyond-brittle)

Going deeper than existing wellbores at Newberry, for the first time into the brittle–ductile transition, will test the efficiency of thermally induced fracturing and reservoir creation during the drilling stage. The drilling fluid temperature should remain below 200 °C in order to cool drill bits and logging equipment, which will induce a thermal shock while drilling into hot rocks with temperatures above 400 °C.

In addition, a post-drilling hydraulic well stimulation will both change the pore pressure in fractures and cool the fracture walls. The extent of thermal fracturing and the associated changes in the permeability of the formation remain a big unknown in this kind of thermally activated EGS. Understanding and predicting these processes constitute important factors for development of geothermal energy from supercritical steam (>374 °C, > 22 MPa).

From the standpoint of scientific drilling, the primary goal is to characterize the thermal, hydrologic, mechanical and chemical environment needed to design and execute eventual geothermal success at supercritical conditions, and to do so in a continental setting characteristic of the trans-Pacific ring-of-fire as well as analogous volcanic arc and rift regions.

The NDDP is an initial step towards a commercially viable supercritical EGS project, which would lead to a step change in energy per well, from 5 to 50 MW (Cladouhos et al., 2018), and a commensurate, significant drop in cost per MWh in energy produced.

3.2 Collect samples of rocks within the brittle–ductile transition

The IDDP-2 well in Iceland successfully collected some core at temperatures above 400 °C. The mafic rocks from the IDDP-2 hole are not yet ductile as the brittle–ductile transition (BDT) temperature in rocks is heavily dependent on silica content. Spot core samples were collected from the deep well at Kakkonda, including one that contained the Kakkonda granite (Muraoka et al., 1998). NWG 46-16D will present the rare opportunity to collect silica-rich core (likely young granodiorite) from within the BDT. Note that at the expected temperature, it is anticipated that silica-rich rock will be ductile at tectonic strain rates, but not necessarily for drilling and well stimulation strain rates.

3.3 How Newberry Volcano works

The U.S. Geological Survey (USGS) considers Newberry Volcano to be a very high-threat volcano because of its recent volcanic activity (within the past 1500 years) in an area where numerous people live. According to a USGS fact sheet, which calls Newberry Volcano a "Sleeping Giant" (Donnelly-Nolan at al., 2011), the volcano hazards at Newberry include

- lava flows,
- ash, pumice, and cinders,
- pyroclastic flows, and
- earthquakes and faulting.

In the recent geologic history of Newberry Volcano there is clear evidence of each of these hazards. For example, eruptions of hot ash, pumice, and gases formed a pyroclastic flow deposit about 75 000 years ago as part of the eruption that created Newberry Caldera.

If drilling under or within a National Volcanic Monument were not precluded by US law, a directionally drilled well targeted towards the magma chamber under the center of the caldera, either through long-reach inclined drilling or from directly above, would probably be the best option from a volcanological point of view. A sub-vertical drill hole outside the monument boundary (the approach used for existing wells 46-16 and 55-29) is an excellent alternative that satisfies the other goals of the project as well as permitting requirements, while providing a high-resolution lithologic column with radiometric dates through deeper formations of the volcano where dykes and intrusions associated with prior eruptions will be intersected. This will help characterize the extent and periodicity of major and minor eruptions in the past and determine the likelihood of their future occurrence. Cores taken in this zone, along with testing and logging, will aid in understanding rock mechanical behavior and the stress regime in the brittle–ductile transition zone where eruptive events originate (see sections below). A deeper thermal profile will also provide an essential constraint for improved thermal models of magmatic systems. In situ measurements of minimum principal stress direction and magnitude are critical for geomechanical models, models of eruption triggering, and models of earthquake triggering. Since there are few direct measurements of stress magnitude in the Cascades, this would be of broad relevance to other magmatic systems and studies of regional tectonics.

4 Mechanisms of magmatic intrusions

The large stratovolcanoes of the Cascades are typically associated with numerous vents that outline large active zones stretching over many kilometers from the axial area (Hildreth, 2007). In some cases, such as the Three Sisters volcanic cluster in Oregon located ~ 60 km northwest of Newberry Volcano, three large volcanic cones stand within a few kilometers of one another and have erupted lavas belonging to the same calc-alkaline suite (Hildreth et al., 2012). These neighboring eruption centers are almost certainly connected to one another, indicating that lateral magma transport is able to channel large magma volumes. Incontrovertible evidence of such transport has been described at Mount Katmai, Alaska (Eichelberger and Izbekov, 2000; Hildreth and Fierstein, 2000), and at Krafla volcano, Iceland (Einarsson and Brandsdottir, 1980). Further support for this process is provided by dyke swarms that emanate from a common focal area and that may be traced over more than 20 km (Odé, 1957). How and at which stage of volcanic activity magmatic plumbing systems grow laterally is an active research concern.

Analysis of surface rock samples at Newberry shows a wide range of igneous rock compositions, dominated by a bimodal concentration of basaltic andesite and rhyodacite. Hundreds of volcanic vents and fissures are located on and adjacent to the volcano, some of which pre-date Newberry. Data from MacLeod et al. (1982), and from deeper temperature boreholes, suggest that the early eruptive history of the edifice was dominated by mafic lava. Over time, the magmatic character changed to the current bimodal basaltic andesite and rhyodacite. The Newberry flows are deposited on older volcanic and clastic sequences, most of which do not outcrop locally. The characterization of these deeper formations will thus be an important objective of the drilling.

In particular, below 2000 m depth beneath the surface, the Oligocene John Day Formation (37–19 Ma) is intruded by many sills and dykes coming from both the modern and ancient magma chambers. This formation is composed of silicic, intermediate, and basaltic volcanic lava flows, rhyolite ash-flow tuff, and dacite to rhyodacite tuffs and alluvial deposits (Robinson et al., 1984). While existing wellbores extend to ~ 3000 m depth, a number of dykes and plutonic bodies at depths greater than 3000 m beneath the western flank are inferred from geophysical data. The current Newberry Caldera formed 75 000 years ago, and Newberry Volcano is generally considered to be 600 000 years old. The McKay Buttes, 580 000-year old rhyolite domes 10 km WSW of the current caldera center, are now mostly buried by Newberry lavas. Granodiorite from cuttings in NWG 55-29 were recently dated as 1.9 Ma (much older than Newberry), while granodiorite from another deep well, 86-21, was dated as 385 ka (Newberry aged) (Julie Donnelly-Nolan, personal communication, 2017). Thus, it is likely that the location of today's Newberry Caldera has been preceded by older calderas, and there may have also been older volcanoes at this location with eastward migration of the volcanic center over time. The record of previous magma chambers, volcanoes, and eruption could be preserved in still warm intrusive bodies on the western flank below NWG 46-16. These potential sources of heat have yet to be confirmed by drilling. The identification, characterization and dating of these intrusive bodies, as well as the determination of the main control factors of their emplacement and extension, constitute a major scientific objective that can only be reached by deep drilling. Their role in the fracturing of the host rock and in the dynamics of the overall magmatic system will also be considered.

4.1 Geomechanics close to a magmatic system

The geometry and orientation of structural features, such as fractures, faults, and dykes, on a volcano are a function of the in situ stresses, which are likely to be heterogenous both spatially and temporarily. Likewise, successful design and execution of an EGS project on a volcano will depend upon accurate knowledge of the stress regime. Stress models have been a challenge at EGS projects associated with volcanic systems in the past, starting at Fenton Hill (see the recent reanalysis by Norbeck et al., 2018) and continuing with Hijiori and Ogachi basin (Kaieda et al., 2010). Even at conventional geothermal fields in extensional regimes (i.e., Dixie Valley, Hickman et al., 1998), the stress can be heterogeneous in a single well. A mini-frac test, or extended leak-off test, is a pressurized in situ stress test that provides information about a rock reservoir's permeability, mechanical strength, and especially the minimum principal stress. Developing and testing new, more reliable and easily performed methods of measuring stress in geothermal wells will be an important R&D result.

4.2 Calibration of geophysical imaging techniques

The conceptual geological model built on independent geophysical observations and models includes large intrusive bodies below the deepest wells in the western flank of Newberry. Drilling a well to ~ 5 km will allow verification of these interpretations, as well as validation of bounds placed on the temperature and permeability of these deeper formations. This will help define the best imaging tools that could be deployed in such a geological context, their optimal resolution, as well as their distribution in the field. This will have enormous value for future geophysical exploration and EGS monitoring efforts, and for understanding of the evolution of volcanic systems and related volcanic hazards.

4.3 Drilling and geophysical monitoring in a high-temperature environment

Drilling in very high-temperature environments, potentially with supercritical fluids, is a difficult task as demonstrated by the IDDP-1 experiment (Pálsson et al., 2014) and requires special drilling bits, drill string, casing and cement, as well as a rigorous environmental, health, and safety plan. The most innovative techniques available on the market at the time of the drilling will be evaluated and tested. In particular, the technique for collecting core samples (i.e. spot cores or continuous wireline coring) needs further evaluation during the pre-drilling phase of the project. Well deviation, temperature, ability to cool the well through circulation and the hourly rig cost during coring will be critical factors that will be analyzed in choosing a coring method. Another issue related to the extreme temperature is the mechanical behavior at the drill face, that is, whether the brittle–ductile transition can be detected.

Downhole geophysical tools should also have exceptional tolerance at high temperatures and pressures, and durability in chemically aggressive fluid environments (Ásmundsson et al., 2014). For example, what is the extreme limit of deployment of fiber-optic based technologies that are now increasingly used in subsurface projects? During the NDDP, we propose to test different instruments and methods like high-temperature fiber-optic microseismic arrays, distributed well monitoring for production, and deep borehole electrical resistivity tomography (ERT) electrodes.

4.4 Why drilling?

It will be extremely challenging to drill rocks hotter than 450 °C. Above the critical point of water, flow-back fluids will be much more corrosive and dangerous, requiring special casing and wellhead alloys. Some rocks will begin to exhibit ductile behavior, making drilling and injection testing more unpredictable. Instruments that can withstand these conditions are limited and expensive.

As described above, the goals of the NDDP are to (1) test the EGS above the critical point of water, (2) collect samples of rocks within the brittle–ductile transition, (3) investigate volcanic hazards, (4) study magmatic geomechanics, (5) calibrate geophysical imaging techniques, and (6) test technology for drilling and geophysical monitoring in a high-temperature environment. None of these goals can be achieved in a laboratory or otherwise without drilling. Drilling is the only way to prepare a hole for testing a large-scale EGS at supercritical temperatures. Drilling is the only way to collect in situ materials (cuttings, core, fluids) through the BDT. Drilling is the only way to measure in situ properties that control volcanic hazards such as principal stress magnitudes and orientation. Drilling is the only way to test in situ geomechanics by perturbing the rock mass through well stimulation. Drilling is ultimately the only way to test drilling equipment and casing outside of the lab, to refine and prove the technologies that will be needed to develop Super Hot Geothermal projects.

5 Scope of the proposed drilling

The Newberry Deep Drilling Project will be located at an idle geothermal exploration well, NWG 46-16, drilled in 2008, 3500 m deep and 340–374 °C at bottom, which will be deepened another 1000 to 1300 m to reach 500 °C into the supercritical region, and potentially approaching the brittle–ductile transition or even zones of partial melt. The original well was drilled with few lost circulation zones and the temperature profile indicates conductive heat flow. Compared to other Super Hot Geothermal projects worldwide (e.g., Reinsch et al., 2017), this well would return more materials (cuttings, core and fluids) with more predictable drilling conditions, thus providing a suite of data near and across the brittle–ductile transition in silica-rich rocks. After drilling, a hydraulic well stimulation will both change the pore pressure in fractures and cool the fracture walls, resulting in permeability enhancement through both thermal fracturing and hydro-shearing. Zonal isolation resistant to this temperature range will be developed and tested.

Geothermal, volcanic, geophysical, and engineering information gained will be widely applicable across the Cascade volcanic arc, as well as other magmatically active areas throughout the Pacific Rim and beyond. 46-16D will be completed with casing and cement designed and tested to withstand the abuses of thermal cycling, hydraulic and thermal stimulation, and flow of supercritical fluids.

A detailed plan with contingencies will be developed during the pre-drilling planning and qualification phase of the project. Details below are subject to change based on further data analysis and technological review. Pre-drilling due diligence for risk assessment will include mechanical integrity testing of the existing 34 cm (13.375-inch) casing and investigation with a camera run of a blockage at 1525 m that formed during a flow test in October 2008 and then was easily re-opened by a drill bit. Then, depending on the nature of blockage, a workover rig will be brought in to clean it out and potentially case off the unstable zone.

The preliminary drilling and completion plan is to deepen the well to at least 3750 m with 31.12 cm (12.25-inch) bits, the depth at which a temperature of 374 °C (the critical point of pure water) is expected. Then the well will be cased with 24.45 cm (9.625-inch) casing tied back to the surface. The detailed procedures, and casing and grouting materials, for this very challenging step will be developed and independently reviewed during the pre-drilling planning and qualification phase of the project. The hole will be deepened to an expected depth of 4877 m and temperature of 500 °C. Based on geophysical models (Bonneville et al., 2017), 46-16D is expected to intersect granitic rocks between the current TD and 4000 m. Cores will be collected at regular intervals and stress measurements as allowed by the technology and drilling conditions. A 17.78 cm (7-inch) perforated liner will be installed in the open hole interval, 3650 to 4877 m. After well completion, a 2-week rig-on hydraulic and thermal stimulation will be performed with design parameters informed by core analysis, THMC modeling, and laboratory testing. EGS creation will be monitored by an improved micro-seismic network as well as by surface and borehole geophysical methods (MT, ERT, InSAR, microgravity). To finish, a single-well flow-back test will be performed to determine well permeability and EGS success.

6 Future development

For 15 January 2019, the authors plan to submit a full drilling proposal to ICDP which will incorporate most of the results of the thorough discussions held during the workshop. If accepted, this proposal would cover part of the funding for the scientific aspects of drilling. In addition to that, the project team has developed an extensive, multi-pronged plan for obtaining the remainder of the funding from public agencies and a variety of interested parties. For the purposes of management and investment, the fundraising will be separated into three categories: technology, science and development.

Data availability. Most data supporting the work presented in this report are available in the US Department of Energy Geothermal Data Repository (GDR): https://gdr.openei.org/home, last access: 10 October 2018.

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Scientific Drilling
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Global monsoon and ocean drilling

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Abstract. The IODP-PAGES Workshop on Global Monsoon in Long-term Records was held on 7–9 September 2017, in Shanghai, China. Forty-eight scientists from 12 countries exchanged scientific findings from the seven recent IODP monsoon-related expeditions (see Table 1), discussed future research directions, and strongly recommended that monsoon system behavior be included in a future IODP initial science plan because it is one of the most active factors in the global climate system and crucially influences the global hydrological cycle.

1 Paleo-monsoon in IODP

Over the last 2 decades, there has been a dramatic increase in research activities and in the number of publications devoted to monsoon variability. Speleothem and ice-core records, together with deep-sea and terrestrial sediments, have enhanced the resolution of paleoclimate proxy records to an unprecedented level. In recent years (2013–2016), seven deep-ocean drilling expeditions were completed by IODP (Integrated Ocean Drilling Program and International Ocean Discovery Program) to explore the Cenozoic history of the Indian, East Asian and Australian monsoons (Fig. 1, Table 1). Earlier, between 1986 and 1999, at least 10 ODP (Ocean Drilling Program) cruises carried out drilling in African, American and Asian monsoon regions as well (Fig. 1, Table 2).

Traditionally, the variability of the monsoon has been studied almost exclusively on regional scales, by both the modern and paleo-monsoon communities. With the application of remote sensing and other new techniques over the last decade, the concept of the global monsoon has been introduced as a global-scale seasonal reversal of the three-dimensional monsoon circulation associated with the migration of rainfall in the monsoon trough and the intertropical convergence zone (ITCZ) (Trenberth et al., 2000; Wang and Ding, 2006). In an effort to understand better the dynamics of monsoon variability, the "Global Monsoon and Low-Latitude Processes: Evolution and Variability" working group was established by PAGES (Past Global Changes) in 2007.

This working group conducted two successive symposia in 2008 and 2010 in Shanghai (Wang et al., 2009, 2012a), bringing together paleo and modern climatologists, as well as data producers and modelers. They compared monsoon studies from all regional monsoon systems and identified their similarities and differences across an exceptionally broad range of timescales, from interannual to tectonic, and tried to unravel the mechanisms causing variations in the global monsoon system and regional monsoon deviations from the global trend. As a result, a special issue with 13 contributions (Wang et al., 2012b) and two synthesis papers (Wang et al., 2014, 2017) were published. Obviously, the relevant community felt that the time was right for an international workshop to synthesize the research progress of monsoon-related IODP and ODP expeditions from a new viewpoint of the global monsoon system.

2 The IODP-PAGES Workshop

After 2 years of preparation, the IODP-PAGES Global Monsoon Workshop took place on 7–9 September 2017, in Shanghai, co-sponsored by IODP, PAGES and IODP-China. Forty-eight scientists from 12 countries participated in the workshop, presented the scientific findings from the seven recent IODP monsoon-related expeditions (Table 1) as well as the previous ODP cruises (Table 2), discussed research

Table 1. IODP monsoon expeditions.

IODP	Topic	Dates	Drill Sites	References
346	Sea of Japan, East China Sea: Asian monsoon	Jul–Sep 2013	U1422–U1430	Tada et al. (2015)
353	Bay of Bengal: Indian monsoon rainfall	Nov 2014–Jan 2015	U1443–U1448	Clemens et al. (2016)
354	Bengal Fan: Himalaya and climate	Jan–Mar 2015	U1449–U1455	France-Lanord et al. (2016)
355	Arabian Sea: tectonic-monsoon interactions	Mar–May, 2015	U1456–U1457	Pandey et al. (2016)
356	Indonesian Throughflow	Jul-Sep 2015	U1458–U1464	Gallagher et al. (2017)
359	Sea Level, Currents, and Monsoon Evolution in the Indian Ocean	Sep–Nov 2015	U1465–U1472	Betzler et al. (2017);
363	Western Pacific Warm Pool	Oct–Dec 2016	U1482–U1490	Rosenthal et al. (2017)

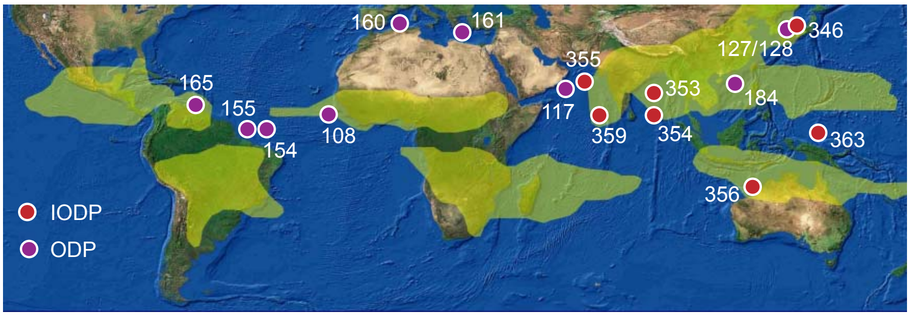

Figure 1. IODP/ODP monsoon expeditions.

directions, and made recommendations for the future IODP science program (Fig. 2).

The workshop started with presentations given by the PAGES Global Monsoon Working Group. On the basis of observation and proxy data, the working group found that the regional monsoons can vary coherently, although not perfectly, at various timescales. Monsoon variability may arise from external forcings or internal feedback processes within the climate system (Fig. 3). Within the global monsoon system, each subsystem has its own features, depending on its geographic and topographic conditions. Discrimination between global and regional components in the monsoon system is a key to revealing the driving factors in monsoon variations.

In the IODP Science Plan for 2013–2023, investigating the monsoon is listed in "Challenge 3", essentially as a factor controlling the regional patterns of precipitation (IODP, 2011). Accordingly, the recent monsoon-related IODP expeditions largely focused on the variations of the global hydrological cycle. For example, ocean drilling addressed this topic beginning ~30 years ago with ODP Leg 117 to the Arabian Sea, which established a regional paleo-monsoon history from monsoon wind-driven upwelling records. IODP Expedition 353 in 2014 targeted paleo-monsoon reconstruction based on salinity gradients induced by summer monsoon precipitation (Clemens et al., 2016). In the Sea of Japan during ODP Leg 127, a 0.9 Ma sequence recovered 30 years ago was marked by alternation of dark and light layers in deep-water sediments, ascribed to millennial-scale variability of East Asian summer precipitation. In 2013, IODP Expedition 346 recovered a much longer monsoon record back to the middle Miocene at about 12 Ma (Tada et al., 2015). In general, ODP-IODP drilling has yielded the longest high-resolution records of regional monsoons, providing the basic data for a global synthesis of monsoon variations from tectonic, orbital, down to millennial timescales.

3 Scientific recommendations

A number of questions were discussed during the workshop, such as applicability of the global monsoon concept at geological timescales, monsoon response to external forcing and internal feedback, initiation of the current monsoon systems, the use and interpretation of monsoon proxies, and the role of monsoonal circulation in the global climate system. In order to promote the development of global monsoon research and to elucidate its role in the hydrological cycle at various geological timescales, the workshop came up with the following recommendations for future IODP activities to be incorporated into the IODP Science Plan beyond 2023.

3.1 To include global monsoon in the future IODP science plan

Monsoons have been included in the current IODP Science Plan, where "Challenge 3" reads as "What controls regional patterns of precipitation, such as those associated with monsoons or El Nino?" (IODP, 2011). Successive monsoon-

Table 2. ODP monsoon expeditions.

Monsoon	Leg	Sea area	Drill sites	Year
Northern African	108	Equatorial Atlantic	657–668	1986
	160	Eastern Mediterranean	963–973	1995
	161	Western Mediterranean	974–979	1995
South American	154	Ceara Rise	925–929	1994
	155	Amazon Fan	930–946	1994
	165	Caribbean Sea	1002	1996
Asian	117	Oman margin	720–731	1987
	127/128	Sea of Japan	794–799	1989
	184	South China Sea	1143–1148	1999

Figure 2. Participants of the IODP-PAGES Global Monsoon Workshop.

related expeditions in recent years provided an unprecedented opportunity to address these fundamental and societally critical questions, and overcome the challenge that the study of paleo-monsoons typically has been addressed or investigated as a regional supplement to the glacial cycles. Recent, transformational work, in contrast, emphasized the global nature of the monsoon system revealed by modern climatology and by recent findings in paleoclimatology. Although monsoon precipitation accounts for only 1 / 3 of the modern global total rainfall, its spatial–temporal variation is the most mutable component in the global hydrological cycle, ranging from inter-annual to geological timescales. Together with ENSO and trade winds, the global monsoon comprises a major low-latitude component of the world climate system, and thus may provide a key to understanding the controlling factors of the hydrological cycle. Therefore, monsoon study should enter into the future IODP science plan as a global system with a strong influence on the global hydrological cycle.

3.2 To recover deep-time monsoon records in high resolution

Despite excellent progress in generating high-quality records over the past decade, the majority of high-resolution paleomonsoon records remain restricted to the late Quaternary, with only a limited number of sediment sequences at several IODP sites tracing back beyond the Pliocene. A much longer time coverage is urgently needed to reveal monsoon changes over the hot-house to ice-house transition in the Oligocene, and the tectonic background of when and how the modern monsoon systems were established. Some of these target sections could be accessed by deepening previously drilled ODP/IODP sites. These types of targets will provide information on the equilibrium response of monsoon sys-

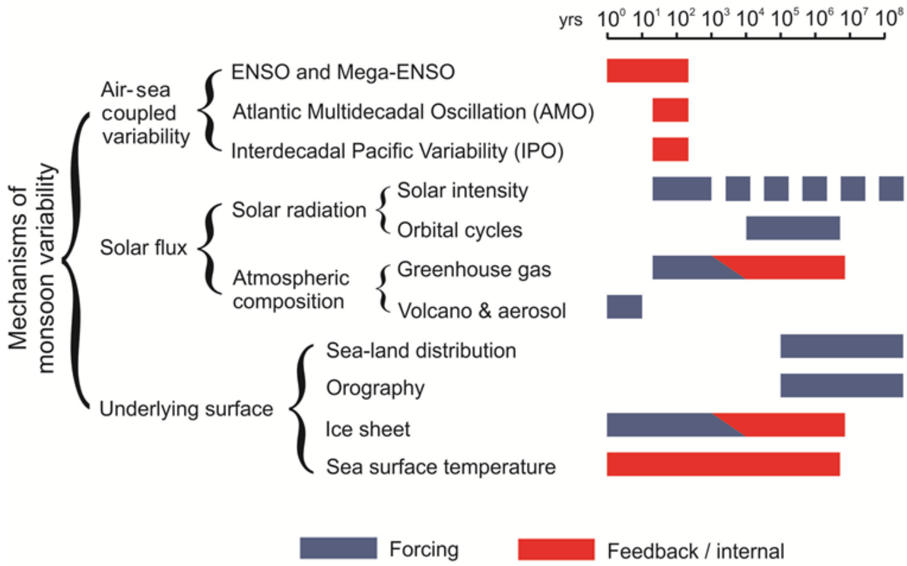

Figure 3. Mechanisms of global monsoon variability and their timescales (Wang et al., 2017).

tems to large-scale boundary conditions (CO_2 and global ice volume), fundamentally different from the rapidly evolving Plio-Pleistocene conditions.

3.3 To develop and verify monsoon proxies

A crucial issue is the accurate interpretation of monsoon proxies. Chemical and isotopic proxies have been extensively and successfully used in paleo-monsoon reconstructions, but opinions on their interpretation are divergent. The scientific debates call for further calibration of the current proxies and for development of new proxies, especially those indicative of the global monsoon as a climate system (see Wang et al., 2014, 2017, for a review). As many scientists working in monsoon regions tend to interpret all variance in the context of monsoon circulation, it is essential to discriminate the components of climate changes related to monsoon variability from those unrelated to monsoon variability. Progress requires integration across different disciplines working on the same monsoon questions from very different approaches, including geochemical, sedimentological and biological approaches.

3.4 To extend geographic coverage of ocean drilling

The existing deep-sea monsoon records are heavily biased to the Northern Hemisphere. High-resolution, pre-Quaternary records are urgently needed from the Southern Hemisphere, including monsoon areas off South America, Australia and South Africa. We expect that future targets of paleo-monsoon studies will continue to have a strong focus on margin environments, quite often located within exclusive economic zones. This will require enhanced focus on the part of IODP and its successors to initiate, develop, and nurture international relationships required to gain access to these regions. One possible solution is to find a way to extend the present IODP membership into developing countries without sharing the financial burden.

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

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Workshop Reports

IODP workshop: Core-Log Seismic Investigation at Sea – Integrating legacy data to address outstanding research questions in the Nankai Trough Seismogenic Zone Experiment

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Abstract. The first International Ocean Discovery Program (IODP) Core-Log-Seismic Integration at Sea (CLSI@Sea) workshop, held in January–February 2018, brought together an international, multidisciplinary team of 14 early-career scientists and a group of scientific mentors specialized in subduction zone processes at the Nankai Trough, one of the Earth's most active plate-subduction zones located off the southwestern coast of Japan. The goal of the workshop was to leverage existing core, log, and seismic data previously acquired during the IODP's Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), to address the role of the deformation front of the Nankai accretionary prism in tsunamigenic earthquakes and slow slip in the shallow portion of the subduction interface. The CLSI@Sea workshop was organized onboard the D/V *Chikyu* concurrently with IODP Expedition 380, allowing workshop participants to interact with expedition scientists installing a long-term borehole monitoring system (LTBMS) at a site where the workshop's research was focused. Sedimentary cores from across the deformation front were brought onboard *Chikyu*, where they were made available for new description, sampling, and analysis. Logging data, drilling parameters, and seismic data were also available for investigation by workshop participants, who were granted access to *Chikyu* laboratory facilities and software to perform analyses at sea.

Multi-thematic presentations facilitated knowledge transfer between the participants across field areas, and highlighted the value of multi-disciplinary collaboration that integrates processes across different spatiotemporal scales. The workshop resulted in the synthesis of existing geophysical, geologic, and geochemical data spanning IODP Sites C0006, C0007, C0011 and C0012 in the NanTroSEIZE area, the identification of key outstanding research questions in the field of shallow subduction zone seismogenesis, and fostered collaborative and individual research plans integrating new data analysis techniques and multidisciplinary approaches.

1 Introduction

Subduction zones account for 90 % of global seismic moment release and generate damaging earthquakes and tsunamis with potentially disastrous effects on heavily populated coastal areas (e.g., Lay et al., 2005; Moreno et al., 2010; Simons et al., 2011). Seismologic, geodetic, and borehole observatory data from subduction zones throughout the globe indicate that the shallow portion of the subduction zone may accumulate and release strain through a variety of deformation mechanisms (seismogenic slip, creep, slow slip, tremor) over a range of timescales (seconds, weeks, months, years; Peng and Gomberg, 2010).

The Core-Log-Seismic Integration at Sea (CLSI@Sea) workshop was held from 12 January to 7 February 2018 onboard D/V *Chikyu* in the Nankai Trough subduction zone, off southwestern Japan. This workshop was developed to enhance multidisciplinary research to address the role of accretionary prism frontal deformation in tsunamigenic earthquakes and slow slip in the shallow portion of the subduction interface. A singular aspect of CLSI@Sea lay in the fact that it was designed to leverage existing archives of IODP cores and logging data and associated seismic datasets previously acquired as part of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) program. Recent findings from the 2011 Tohoku-Oki mega earthquake in the Japan Trench indeed provided evidence that tsunamigenic slips can be continuous from the locked portion of the subduction plate boundary all the way out to the trench (Chester et al., 2013). Similar behavior has been previously documented in the shallow portion of the Nankai subduction zone (Kinoshita et al., 2009; Sakaguchi et al., 2011; Ito et al., 2013), within the NanTroSEIZE study area, thus highlighting the interest in re-investigating archived NanTroSEIZE data to characterize the nature of fault slip and strain accumulation, fault architecture, and state variables throughout subduction plate boundary systems.

The CLSI@Sea workshop represented an original approach in several aspects. First, CLSI@Sea was an unprecedented opportunity to examine legacy data from multiple former expeditions in the context of a mission not dedicated to core recovery. CLSI@Sea workshop was the first of its kind organized concurrently with an International Ocean Drilling Program (IODP) expedition. Expedition 380 installed a long-term borehole monitoring system (LTBMS) at Site C0006, above the deformation front of the Nankai accretionary prism, thus allowing workshop participants to investigate archived data from the site where the IODP expedition was focused and interact with the expedition science party. Second, a challenging aspect of the workshop was to connect a group of science mentors with extensive experience in the Nankai margin with early-career researchers from diverse research backgrounds (Table 1), to work on common research questions. Third, workshop participants were given the opportunity to pursue new research while onboard *Chikyu*, thanks to full access to shipboard laboratory facilities to re-investigate the IODP archived data. Well-preserved sedimentary cores were brought onboard *Chikyu* from the Kochi Core Center and made available for laboratory analyses. Seismic reflection, log, and drilling parameter data were also kindly provided to all workshop participants onboard.

The international team of workshop participants was then able to develop interdisciplinary discussions and organize both individual and collaborative research plans to address outstanding questions regarding seismogenic-, tsunamigenic- and slow-slip processes in the Nankai subduction zone, a crucial topic for the regional tectonics, but also a fundamental aspect of the Earth's geodynamics.

2 Background and geological setting

The Nankai Trough is formed by the subduction of the Philippine Sea Plate beneath the Eurasian Plate, forming the Nankai prism by the accretion of the Shikoku Basin oceanic plate sediments (Fig. 1). The complex geodynamic evolution of the Shikoku Basin, including the migration of the boundaries of the Amurian, Pacific and Philippine plates over time (e.g., Moore et al., 2015), has resulted in large lateral variations in basement relief, with associated variations in the nature and thickness of sediments, resulting in structures highly variable laterally within the accretionary prism (Fig. 1). In cross section (Fig. 2), the deformation front is located at the toe of the prism, at the boundary with the deepest part of the trough. Upslope from the prism toe (Fig. 2), several landward-dipping imbricated thrusts and associated anticlines and back-thrusting branches form together the Im-

Table 1. CLSI@Sea participants, D/V *Chikyu*, IODP 380, Nankai Trough, 12 January–7 February 2018.

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bricate Thrust Zone (ITZ; Park et al., 2002; Moore et al., 2009). The thrusts of the ITZ sole into the basal *décollement*, corresponding to a strong continuous positive polarity reflection on the seismic reflection data. A potential inactive *décollement* occurs ~ 500 m above the active one in a zone of the low P-wave velocity zone that may correspond to underplated hemipelagic material (Kamei et al., 2012). Beneath the upper slope, two distinctive branches of a first-order thrust correspond to the Mega-Splay Fault (MF; Park et al., 2002, 2010). The MF cuts across the older part of the accretionary prism and can be traced deep (~ 10 km) toward the top of the subducting plate (Fig. 2). The MF extends more than 120 km along strike (Fig. 1; Moore et al., 2007; Park et al., 2010) and is strongly suspected to be one of the primary coseismic faults that may have contributed to generating devastating historic earthquakes and tsunamis (Tanioka and Satake, 2001; Kikuchi et al., 2003; Wang and Hu, 2006). Landward of the MF, the oldest parts of the prism are overlain by marine sediments accumulated in the Kumano forearc basin, bounded to the southeast by a topographic valley at the limit between the basin and the upper part of the trench slope (Fig. 2). This valley corresponds to the Kumano Basin edge fault zone (KBEFZ) that may have a combination of normal and strike–slip faults (Martin et al., 2010).

The Nankai subduction zone has a 1300-year historical record of recurring tsunamigenic earthquakes, including the 1944 Tonankai M_w 8.2 and 1946 Nankai M_w 8.3 earthquakes (Fig. 1), and has been the focus of worldwide marine scientific surveys, including the NanTroSEIZE drilling program. NanTroSEIZE focuses on the Kumano transect of the Nankai accretionary prism (Fig. 2). To date, the program has involved 11 oceanic expeditions, 13 sites of coring and logging, collection of 2-D and 3-D seismic data, and installation of a network of LTBMS' recording in situ data within the Nankai accretionary prism. Collectively, these data provide an unprecedented record of the margin's stratigraphic and structural evolution. Within the NanTroSEIZE study area, Sites C0006 and C0007 (IODP Expeditions 314 and 316;

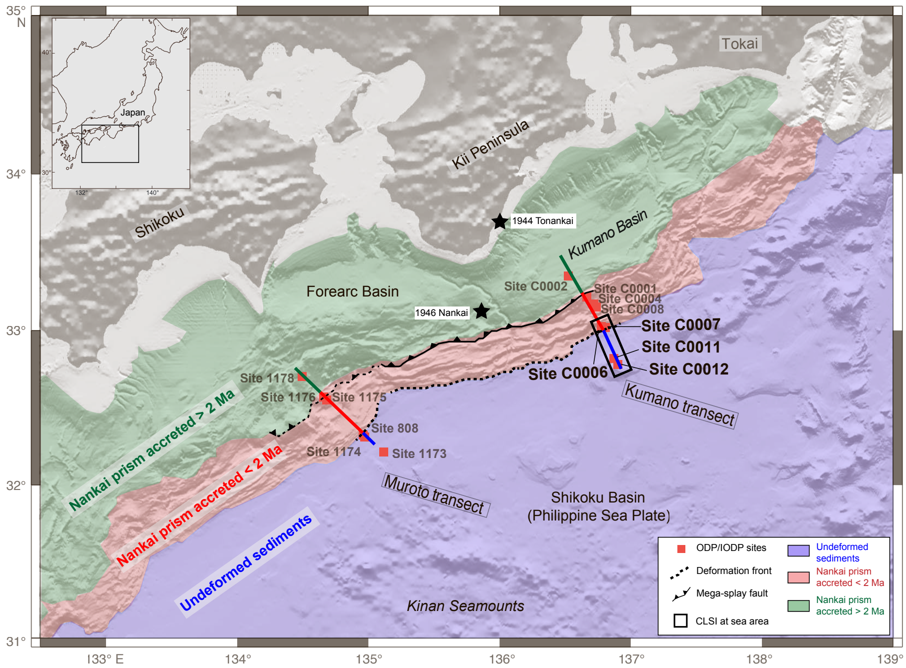

Figure 1. Synthesis map of the Nankai Trough offshore southwestern Japan. The area of investigation of the CLSI@Sea workshop corresponds to the black frame, including Site C0006, the target of IODP Expedition 380. The colors show the stage of evolution of the deformation within the Nankai Trough. The two sections across the Kumano and Muroto transects are shown in Fig. 2. Compiled and modified from Kimura et al. (2014) and Moore et al. (2001, 2009).

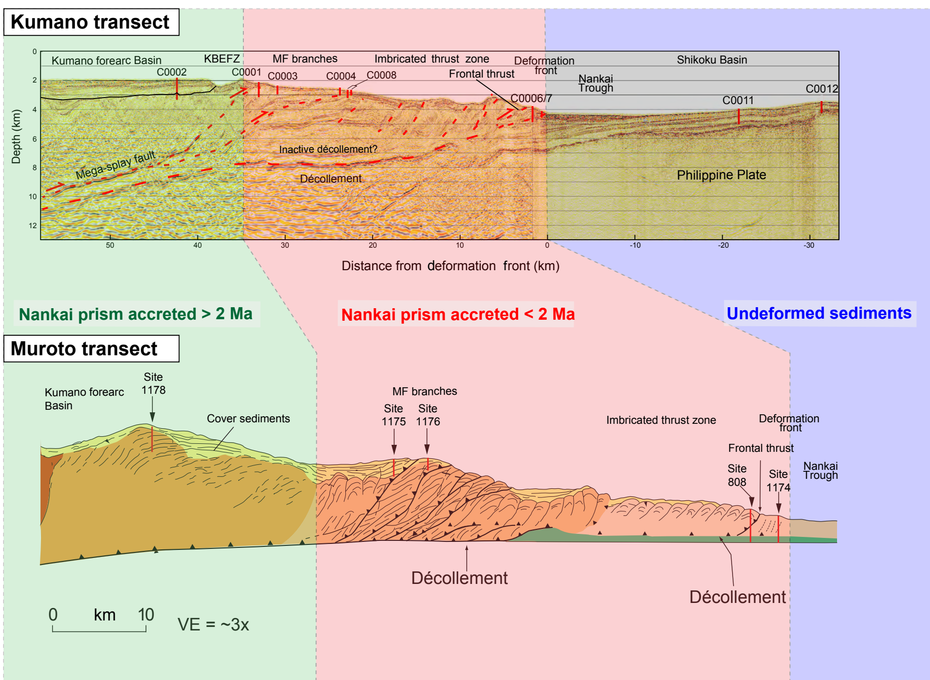

Figure 2. Synthesis structural cross sections across the Nankai accretionary prism along the Kumano and Muroto transects. See location in Fig. 1. The colors are the same as Fig. 1 and refer to the stage of evolution of the deformation within the Nankai Trough, namely, blue: non-accreted sediments; red: accreted sediments less than 2 My ago; green: accreted sediments more than 2 My ago. Modified from Moore et al. (2001) and (2009).

Kimura et al., 2008; Kinoshita et al., 2008 and 2009) located at the deformation front of the Nankai accretionary prism (Fig. 1), and Sites C0011 and C0012 (IODP Expeditions 322, 333, and 338; Underwood et al., 2010; Henry et al., 2011; Strasser et al., 2014), located oceanward of the deformation front, were key targets for the CLSI@Sea workshop to investigate the most recent deformations within the prism toe. In addition, Site C0006 is considered to be outside of the major earthquakes' nucleation zone (Hyndman and Wang, 1993; Oleskevich et al., 1999). However, normal and slow earthquakes (low-frequency tremors, very low-frequency earthquakes, and slow slip events) all seem to possibly occur inside the core sample zone of Sites C0006 and C0007. The installation of the LTBMS during Expedition 380 provides the opportunity to collect data to facilitate understanding of how the seismic slips are controlled at this particular zone of the deformation front, possibly one of the most studied areas on Earth in the quest to better understand tsunamigenic earthquake processes. Equally, the purpose of the CLSI@Sea program is to enhance understanding of this area by re-visiting previously acquired data and core material from the region.

3 Workshop organization

The CLSI@Sea workshop brought together a team of international scientists, mentors and early-career researchers (Table 1) to address outstanding questions on tsunamigenic earthquake processes at plate subduction zones, specifically investigating the Nankai Trough (Fig. 1). A fundamental characteristic of the workshop was the multi-disciplinary expertise of the participants, selected on the basis of their research proposals aiming to investigate different aspects of subduction mechanisms and related processes. Scientific self-introductions during the first days of the workshop were essential to identify the research interests of each participant (Table 1) and develop collaborative research plans based on multi-disciplinary teamwork. Scientific talks given by the mentors and IODP Expedition 380 Co-Chiefs (Table 1) provided an overview of the geological processes identified over the last 10 years at the Nankai subduction zone, at different levels and at different scales of the NanTroSEIZE area, from the seafloor to the top of the subducting plate. Presentations by both mentors and workshop participants helped to trigger discussions and facilitate knowledge transfer between groups, which represented crucial points to identify the key research questions and develop both individual and collaborative research strategies.

Workshop participants developed efficient self-organization, supported by personal initiatives contributing to the CLSI@Sea community research objectives. The participant group self-organized, supported by individual research plans that had been proposed to contribute to the CLSI@Sea program research objectives. As is always the case with highly multi-disciplinary collaborative projects such as IODP, a degree of flexibility and compromise was also required, with initial research plans being modified and adjusted to avoid duplication of effort and to ensure the best fit with the over-arching program objectives. In parallel to personal research plans, group research was undertaken by small teams of participants focused on generating a comprehensive synthesis of previous Nankai Trough research arising from IODP expeditions (see Sect. 4), to help identify any outstanding scientific questions. In addition, this collaborative work extended to the development of a database of the scientific literature generated by previous NanTroSEIZE projects and the submission of this workshop report to promote the international, multi-disciplinary CLSI@Sea initiative.

Personal research projects centred on the analysis of the seismic reflection data, logging data and sedimentary cores from Site C0006 (Holes C, D, E, F), Site C0007 (Holes A, B, C, D) and Site C0012 (Hole A) (see Fig. 1 for location). In particular, Sites C0006 and C0007 provided the opportunity to examine cores from the Pliocene and Miocene sections down to the *décollement* (Figs. 4 and 5) at the deformation front. In line with IODP protocols, sample requests had to be submitted and approval received prior to any sampling and analysis of the core material. Software and data handling training was also provided by laboratory technicians to participants to improve efficiency in executing their research projects while onboard *Chikyu*. These individual and collaborative efforts were supported by daily meetings in which the mentoring team provided workshop participants with input and guidance for their ongoing work. The research projects undertaken by the participants included (Sects. 4 and 5) investigations on an accurate age model for the accretionary prism's frontal thrust development; seafloor/sub-bottom morphological response to subduction along the Nankai Trough; P-wave velocity–porosity relationship in the deformation front area; and multi-dimensional analysis of plate boundary faults.

Finally, CLSI@Sea participants were invited to closely follow the progress of Expedition 380, especially in terms of drilling processes and day-to-day technical challenges occurring during IODP expeditions.

4 Integration of legacy IODP data

The coordination of the synthesis of previous IODP NanTroSEIZE projects made to facilitate the organization of future individual and collaborative research plans resulted in the formation of research teams focused on three main subtopics: lithostratigraphy, tectonic structures of the Nankai prism and physical properties of the deformation front. The goal of these research teams was to build a compilation of the formerly published results in the different sub-topics, and across the different IODP sites investigated during this workshop. This compilation was a fundamental aspect of the

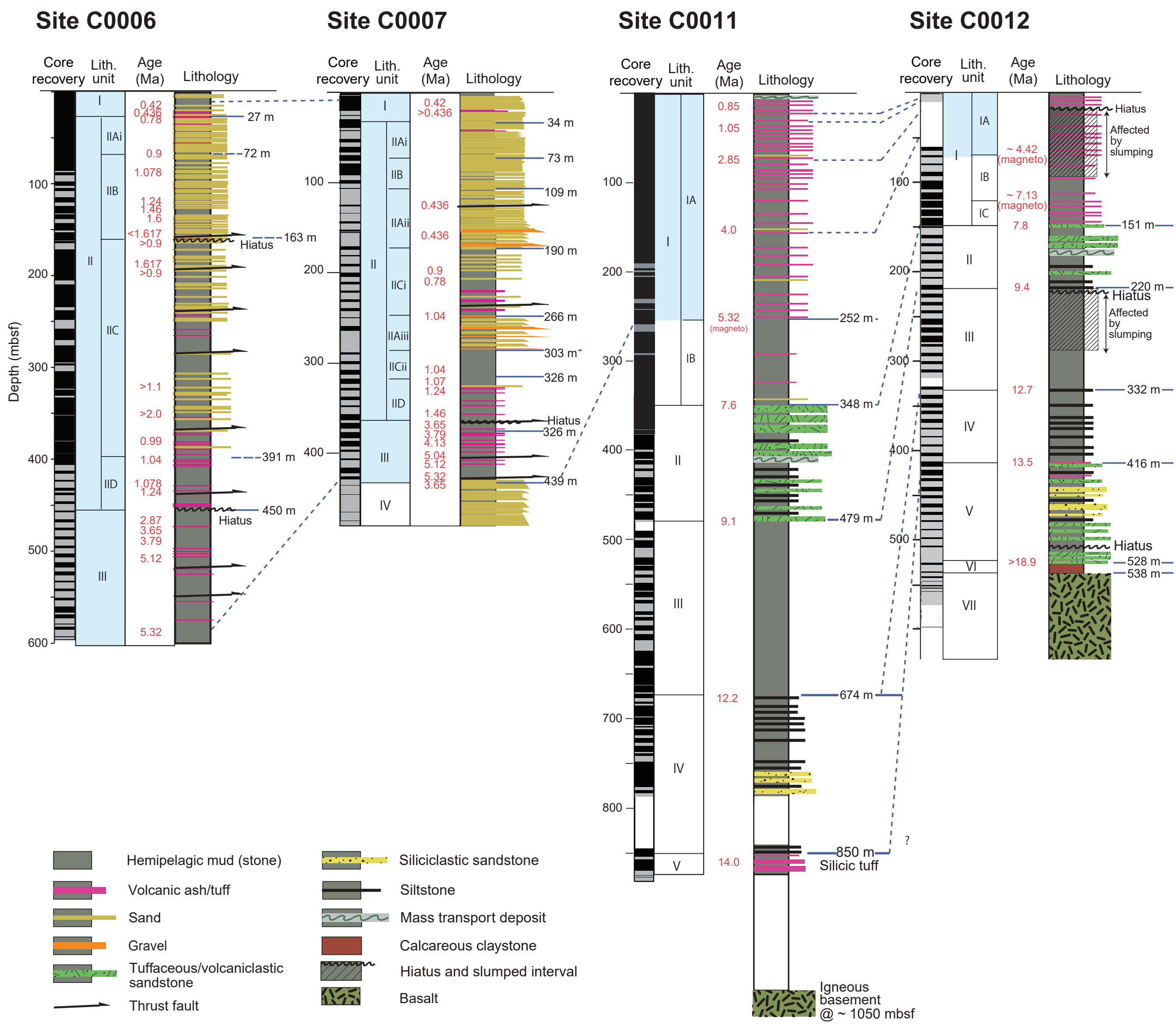

Figure 3. Lithological section across the Nankai frontal prism (Sites C0006 and C0007) and the input sites (C0011 and C0012). The columns at each site show core recovery, lithologic units, sedimentary age, and lithology distribution modified from Kinoshita et al. (2009), Strasser et al. (2014), and references therein.

workshop, to create a state-of-the-art of the existing results and bring up new scientific questions, but also to set up a dynamic work collaboration between the participants.

4.1 Lithostratigraphy of the frontal prism and incoming sediments

The workshop resulted in a new synthesis of the lithostratigraphy and chronostratigraphy for reference Sites C0011 and C0012 and frontal thrust zone Sites C0006 and C0007 (Fig. 3). Reconstruction of the regional sedimentation history and the plate boundary evolution was considered through lithological and stratigraphic analysis of core and data from the incoming Philippine Sea Plate. The original intent of coring ahead of the prism (Sites C0011 and C0012, Fig. 1) was to provide a largely undisturbed record of input sediment cover that could be used to decipher the timing of the formation of the structures at the deformation front (Sites C0006 and C0007, Underwood et al., 2010; Henry et al., 2011; Strasser et al., 2014). The onset of deformation was identified based on the lateral changes in thickness of the upper wedge deposits (lithologic Units I and II in C0006 and C0007, Fig. 3), a key target for scientific questions. During CLSI@Sea, the temporal resolution of stratigraphic units was investigated, and the efficiency of new crystallographic analytical tools to better understand accretionary wedge deformation evolution was tested. Below we briefly summarize the correlated stratigraphy at each site and variations in bulk mineralogical content.

Sites C0011 and C0012 transect the entire incoming sediment sequence of the Shikoku Basin to basaltic ocean crust (Fig. 3) (Underwood et al., 2010; Strasser et al., 2014). Unit I corresponds to late Pleistocene to late Miocene Upper Shikoku Basin deposits, and contains silty clay with minor ash. Unit II is marked by the occurrence of volcaniclastic sandstones in silty claystone and corresponds to late Miocene Middle Shikoku Basin deposits. Units III to V correspond to late to middle Miocene Lower Shikoku Basin deposits. Unit III is a succession of uniform silty claystone and lime mudstone; Unit IV contains silty claystone/clayey siltstone comprising fine-grained, turbiditic sand layers; Unit V contains tuffaceous sandy siltstone with some silty claystone and tuff. The oldest units recovered include calcareous mudstone (Unit IV) overlying oceanic basement basalts (Unit VII). The dominant mineral assemblages are quartz, feldspar, clay minerals and calcite. No major trends in mineral content are observed within Units I and V, but Unit VI has an overall higher clay content and lower quartz and feldspar contents compared to overlying units.

Sites C0006 and C0007 transect accreted Shikoku basin deposits and overlying wedge slope deposits (Kinoshita et al., 2009). Unit I contains unconsolidated hemipelagic mud and turbidites deposited in a wedge slope environment (Kinoshita et al., 2009). Unit II contains alternating sequences of Pleistocene hemipelagic muds and turbidites deposited in a transitional trench–wedge environment. Unit II, which directly overlies the *décollement* at Sites C0006 and C0007, is made up of accreted sediments correlated with the Pliocene to Upper Miocene in the Shikoku Basin. Unit IV, recovered below the *décollement* at Site C0007, consists of a small (~ 15 cm) section of dark, medium to coarse-grained sands. As in Site C0012, the dominant mineral assemblage is feldspar, clay minerals and calcite, and does not display major trends in mineral content.

New investigation and sampling of the sedimentary cores from Sites C0006, C0007 and C0012 during the CLSI@Sea workshop involve the following methods: new tephrachronology/geochronology, clay mineral composition analysis, and macroscopic and XCT re-observation of sedimentary structure. These methods will provide data that will help address the following outstanding questions.

- What is the provenance of accretionary prism body, slope, and fault sediments? How well can we correlate incoming Shikoku basin stratigraphy with off scraped sediments in the frontal prism?

- Is it possible to link the origin of the Nankai prism sediments with the migration of the Philippine Sea–Pacific plate boundary over the Miocene to the present?

- How well can we reconstruct the development and the evolution of the prism from the tectono-stratigraphic framework of the Kumano Basin?

4.2 Tectonic structure of the frontal thrust

The workshop results in a new synthesis of structural features observed in core, log, and seismic data from the incoming plate and frontal wedge of the Nankai prism, including identification of new faulted intervals in the formal prism. The structures of the Nankai prism at the deformation front, where the thrust–fault activity is the youngest (Fig. 1) and the compressional deformation propagates oceanward (Moore et al., 2009; Underwood and Moore, 2012), were examined. Proposed research projects arising from CLSI@Sea and focusing on the structures of the subduction zone included scientific questions related to the timing, amplitude and mechanisms of fault slips, the relationships between deformations and shallow sedimentary processes and their link with potentially tsunamigenic events, especially earthquakes and generation of mass transport deposits. Specifically, the integration and compilation of structural and lithologic data (Fig. 4) across multiple IODP reports and publications allow for the refinement of the presence, extent, and slip history of faults at the deformation front of the prism. Below we briefly summarize structural data from core and log data at Sites C0012, C0006 and C0007 before discussing new observations made during the workshop.

Site C0012 is located seaward of the deformation front. Bedding orientations at this site are dominantly subhorizontal, with intervals of higher angle bedding resulting from gravitational slumping, and high angle fractures resulting from subvertical compaction. Sites C0006 and C0007 penetrated the first two imbricate thrusts at the deformation front, including the main frontal thrust at ~ 700 m LWD depth below seafloor (LSF) (Figs. 2, 3 and 5; Kinoshita et al., 2008, 2009). Bedding at Site C0007 is dominantly subhorizontal, but a major lithologic inversion at ~ 400–450 m b.s.f. places moderately consolidated hemipelagic mudstones over poorly consolidated trench turbidite sands. Site C0006 can be divided into four log units corresponding to distinct structural domains (Fig. 4). Unit I (0–100 m LSF) has generally west-dipping bedding resulting from northwestward tilting driven by plate convergence and southwestward tilting driven by gravitational slumping. Unit II (100–220 m LSF) is a thrust zone that contains several faults identified in core, log and seismic data (Fig. 5). Units III and IV (below 220 m LSF) contain northwestward-dipping beds and fractures, consistent with north-northwestward-directed shortening driven by plate convergence.

In addition to previously reported faults, workshop work resulted in the observation of new faults correlated thanks to the integration of core, log and seismic data (blue strips in Fig. 4). Cores from Sites C0006 and C0007 intersect several major faults, including the plate boundary interface in-

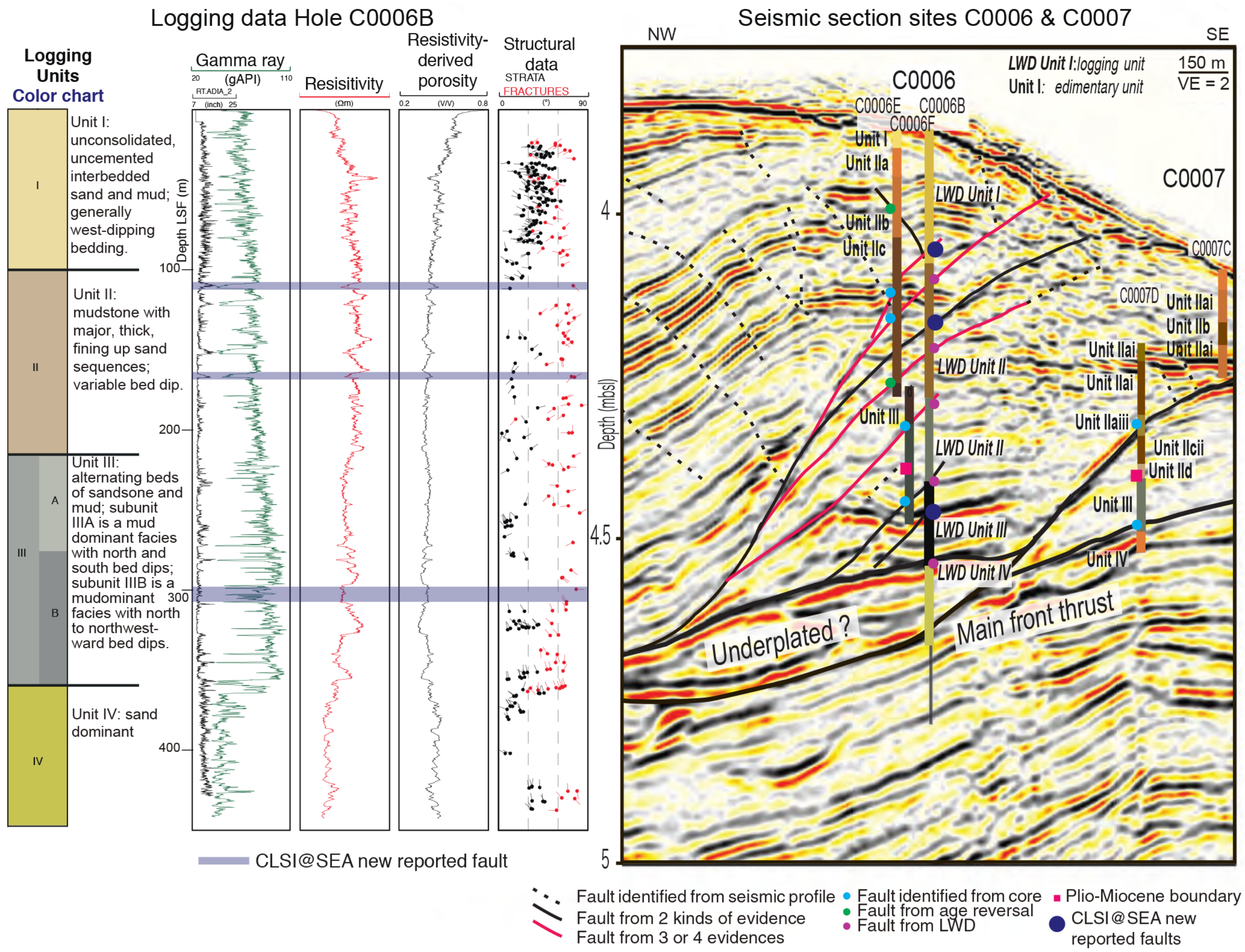

Figure 4. Sedimentary, logging and seismic data at the deformation front of the Nankai prism (Sites C0006 and C0007). Dark blue markers (strips, dots) are additions provided by the CLSI@Sea workshop. The figure shows (from left to right) the logging data at Hole C0006B, the interpreted seismic section (IL 2435) across the Nankai 3-D volume illustrating the structures at the deformation front, and the lithological units and the logging units identified at both Sites C0006 and C0007. Some structures (dark blue) have been identified by integration of the Core-Logging-Seismic data. Figure compiled and modified from Kimura et al. (2008) and Kinoshita et al. (2008, 2009).

tersected at Site C0006 at ∼ 700 m LSF and Site C0007 at ∼ 400 m LSF (Kinoshita et al., 2008, 2009). In the cores, faults largely occur as breccias, gouges, and zones with striated fractures, in which the sense of displacement is often difficult to observe directly. A black gouge-bearing fault zone recovered in the core from Site C0007 at 438 m LSF exhibits a vitrinite reflectance anomaly interpreted to reflect shear heating during past seismic slip to the trench (Sakaguchi et al., 2011). In log data, faults can be identified by simultaneous decreasing of the gamma ray and resistivity values. Cross-comparison of core and log data with 3-D seismic reflection data across the Kumano transect allowed observation of the persistent lateral continuity of the main thrusts across the seismic volume, whereas secondary and tertiary branches of the thrusts show important lateral variations in three dimensions.

Continued structural analysis of the site C0006 and C0007 data involving resistivity log fracture analysis, thin section observations, high-resolution CT scans, re-interpretation of the NanTroSEIZE 3-D volume and geochemical analysis across fault zones will be used to address the following questions.

– What is the temporal history of slip along frontal prism faults? Which sedimentary horizons are offset by thrusts? Do any thrusts breach the seafloor?

– Which structural features exist in the region where seismic tremors have been identified, and which may be genetically linked to tremorgenic processes?

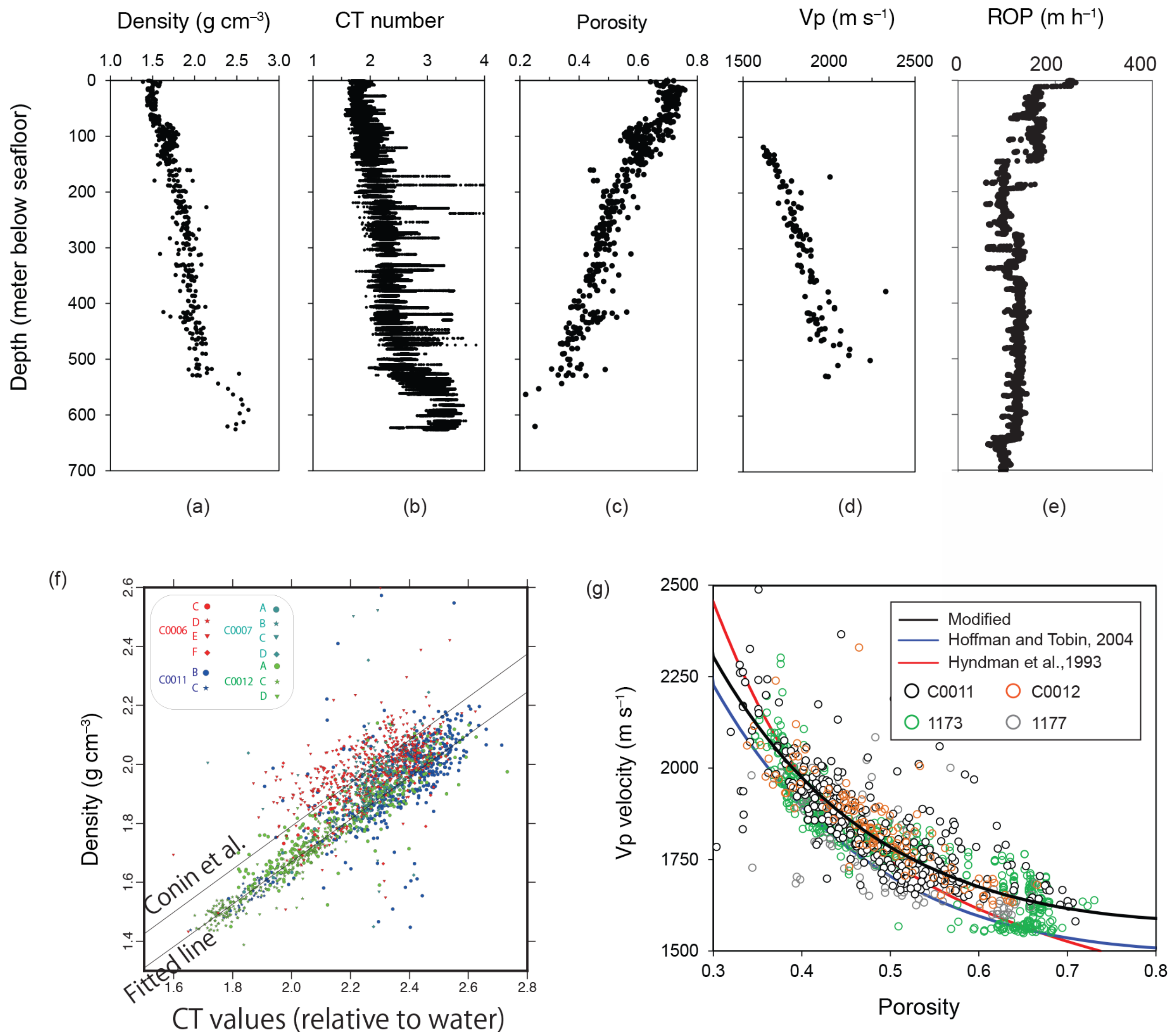

Figure 5. **(a–e)** Density, CT number, porosity, P-wave velocity (V_P), and rate of penetration (ROP) along depth at Site C0012. Density, porosity and V_P data are from discrete samples of Holes C0012A, C0012C, and C0012G. ROP is measured at Holes C0012B and C0012H. CT measurements on cores are from Holes C0012A, C, D, E, F, and G. **(f)** The correlation between CT value and density value at C0006, C0007, C0011, and C0012. **(g)** The correlation of porosity and V_P at Sites C0011, C0012, 1173, and 1177.

- What are the distribution, origin and timing of the mass transport deposits along the Kumano transect and are they temporally linked with fault activity?
- What is the 3-D architecture of the prism? How strong are the lateral variations of the structures within the prism?

4.3 Physical properties in the frontal thrust and incoming plate

The workshop also led to new compilations and analysis of log, computed tomography (CT), and rate of penetration (ROP) data that will promote research on the physical properties (PPs) of the sedimentary units and faults recovered from the cores. These include establishing a relationship between the P-wave velocity (V_P) and the porosity within the sedimentary layers; mapping the physical properties within the prism; estimating stress within the prism; quantifying the frictional heat generated during fault slips, particularly at the *décollement*; investigation of the slip properties along the faults in order to understand the slip behavior from temperatures; and mapping the porosity distribution. PPs of drilled cores are measured onboard *Chikyu* using a Multi-Sensor Core Logger (MSCL) system, discrete-sample measurements, and CT images. Each of these measurements has limitations and was not previously well integrated. For example, the MSCL system can measure PPs of intact and split cores non-destructively, but the measurement is sometimes scattered if the recovered cores are fractured. PPs can also be measured precisely using discrete samples; however, the results from discrete samples are conducted intermittently and only represent a portion of the recovered cores. Concerning CT images, they are taken as a first step before core splitting and are thus able to reveal the continuous internal structure of a drilled core without any destruction. Such images therefore represent a high potential for future studies investigating, e.g., 3-D PPs distributions or fracture mechanics considering small-scale structure around the fault. Compilation and integration of various types of data including CT scan analysis can then provide continuous and more accurate PPs for whole drilled cores. Below we summarize new synthesis and analyses completed during the CLSI@Sea workshop.

Investigations on PPs included analysis on density, porosity, and compressional P-wave velocity of the incoming plate sites (Sites C0011 and C0012, Fig. 1) and the frontal thrust sites (Sites C0006 and C0007). CT values are converted into density using the following equation (Kinoshita et al., 2009):

$$\text{CTvalue} = \frac{f_{\text{material}} - f_{\text{water}}}{f_{\text{water}}} \times 1000,$$

where f_{water} and f_{material} are, respectively, the linear attenuation coefficients of water and the measured material. The attenuation coefficient is a function of the chemical composition and the density of the material. We find that the relation between CT value and density for input sites (C0011 and C0012) lies well on a straight line (Fig. 5), but there is a slight difference from the relation obtained for sites in the accretionary prism (Conin et al., 2014). Although the dependency on lithology and chemical compositions has been investigated in relation to onboard visual core descriptions and X-ray fluorescence analysis, the cause has not been clarified yet. The porosity–depth and porosity–V_{P} relationships in the outboard Sites C0011 and C0012 follow a similar trend to site 1173 (Muroto transect, Fig. 1). Hoffman and Tobin (2004) have shown an empirical relationship of porosity and V_{P} based on the Muroto transect. Here we incorporate the NanTroSEIZE data (C0011, C0012) and define a modified empirical relationship based on Hoffman and Tobin (2004) (Fig. 5). C0006 and C0007 have limited and scattered discrete core data; thus, they are not included to constrain the porosity–V_{P} trend.

ROP is one of the key parameters to assess the drilling efficiency and can be used to estimate the sliding friction coefficient (Pessier and Fear, 1992). We compile ROP at Sites C0006B and C0012H where drilling parameters are available and compare the trend to the core-scale physical properties. The first 100 m of a dataset may not be appropriate for further calculation as there is obvious fluctuation. Future work includes investigation of the impacts of different drilling methods and comparison of the mechanical properties of different lithological units.

The spatial distribution of PPs (especially porosity) contains key information of the degree of compaction and stress states around faults and *décollement*. As an example of CLSI@Sea using compiled PPs, we estimated the porosity distribution along the NanTroSEIZE transect. The V_{P} dataset (Moore et al., 2007; Park et al., 2010) covers the locations from the inner wedge (near Site C0009) to the deformation front (Sites C0006 and C0007) and to the seaward sites (C0011, C0012). We are then able to apply the empirical V_{P}–porosity relationship to estimate the porosity distribution. From the preliminary results, we clearly see that there is a high-porosity zone along the *décollement* associated with the low-velocity zone (Park et al., 2010). This high-porosity zone indicates under-compaction and may suggest high excess pressure during tectonic loading. Future work will include (i) mapping the porosity distribution more precisely by integrating the data in the inner wedge (e.g., Site C0002, Fig. 1), and (ii) estimating the stress and pressure state using the improved porosity distribution results.

Additional post-cruise research involving data compilation, consolidation tests, frictional heating experiments, refinements to velocity structure models and log–seismic correlations will be used to address the following research questions.

- What is the ancient and modern thermal state in the frontal prism, and how is it modified by frictional heating and fluid flows?
- What is the porosity and pore fluid pressure evolution in the accretionary prism, basal *décollement*, and underthrust sediments?
- What are the roles of faults and fractures in fluid circulation within the frontal prism and deformation zones?

5 New findings and opportunities

5.1 Core-log-seismic integration at the deformation front of the Nankai accretionary prism

One of the main objectives of the CLSI@Sea workshop was to provide participants with the opportunity to undertake research based on legacy IODP data acquired in the frontal thrust (Fig. 1, Sites C0006, Holes C, D, E, F, and C0007, Holes A, B, C, D) and outboard regions (Site C0012, Hole A) of the Nankai prism. Through individual and collaborative research, CLSI@Sea participants conducted preliminary analysis during the workshop, using integration of core, logging and seismic data. The cores were brought onboard *Chikyu* for the workshop and made available for sampling, allowing the participants to obtain a total of 519 core samples to analyze the lithological properties, micro-fabrics, grain size distribution, and fracture characteristics.

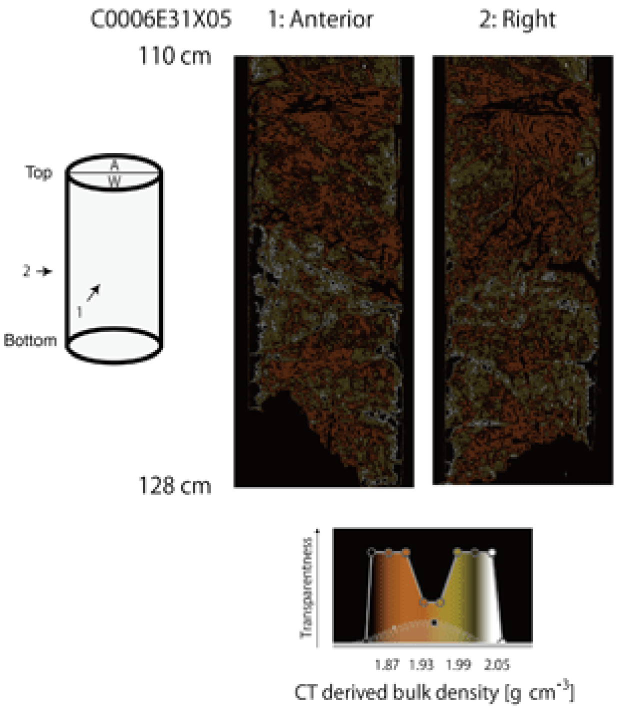

Figure 6. Bulk density distributions converted from the CT value for section C0006E31X05 110–128 cm. Two cross sections through the centre of the core are presented. A 3-D distribution of this section is presented as a movie in the Supplement.

An example of core-log-seismic integration concerns investigations of the fault zone at Site C0006 (Fig. 4). Although several fault zones are reported in the expedition reports of this site (see Sect. 4, Kimura et al., 2008, and Kinoshita et al., 2008, for more details), studies of fault zones so far have mainly concentrated on the Mega-Splay Fault (Fig. 1) and the toe of the *décollement* (Site C0007, Fig. 4). As a first step of the investigation, seismic reflection data have been checked to identify major fault zones with sufficient displacement. The depths of identified faults have then been estimated by studying the logging resistivity images and core CT images. Based on the estimation of the depth of the faults, stored cores have been thoroughly observed, allowing identification of several faults, which were consequently sampled for further analysis.

During CLSI@Sea, we recognized the importance of quantitatively integrating CT images into other data; CT values are indeed meaningful since they reflect the physical and chemical properties of the material as addressed in Sect. 4.3. Despite the great non-destructive advantage of CT images, only a few studies have used the information of CT values in the NanTroSEIZE project so far (e.g., Conin et al., 2014). Figure 6 (and the Supplement) shows the 3-D bulk-density distribution of one identified fault with a proper color scale, which is usually with grey scale in the original CT images (see Fig. 24 of the expedition report by Kinoshita et al., 2009). A 3-D image of CT-value-derived bulk density with millimeter-scale resolution was thus very powerful in identifying potential faults.

5.2 Post-cruise studies

The time spent onboard *Chikyu* during IODP Expedition 380 was the first step of a longer-term renewal of the NanTroSEIZE research program resulting from the CLSI@Sea workshop investigations. Once back in their home institutions (Table 1), CLSI@Sea participants will make progress with their individual and collaborative research projects that were initiated onboard *Chikyu*. The targets of these studies fall into three main scientific fields: (i) lithology and stratigraphy (paleo-temperature, frontal prism and incoming plate stratigraphy, turbidites, sedimentary flow paths, and clay minerals); (ii) tectonic structures (along- and across-strike geometry of thrusts, faults and relationship with the *décollement* and shallow sedimentary processes, age and evolution of the deformation, and fracture distribution); (iii) physical properties (porosity, stress, heat, shear deformation, P-wave velocity, friction, fault slip behavior, and sedimentary consolidation). The future laboratory analysis and experiments on the sedimentary cores sampled onboard *Chikyu* will include optical microscope observation, scanning electron microscope (SEM) observation, energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD) analysis, X-ray CT, triaxial tests, friction experiments, radiogenic decay, and vitrinite reflectance measurements. The logging, seismic reflection, and velocity data will be analyzed using geophysical interpretation tools, and will eventually be correlated with the new results. The successful installation of the LTBMS on Site C0006 during Expedition 380 will also provide additional in situ data for NanTroSEIZE investigators, including real-time pressure, strain, and seismological data. Connection of the Site C0006 LTBMS to the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) cabled network managed by the Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) will allow provision of crucial day-to-day global records of the Nankai prism activity to understand the evolution of the subduction zone.

Discussing all together the different open targets raised within each research sub-group, workshop participants agreed that their correlation of former results (Sect. 4) and future analysis would allow them to answer key questions that can be summarized as follows.

– What governs subduction zone seismogenic fault locking vs. stable-slip and/or transitional fault behavior? Is there an "updip limit" to the seismogenic zone, and what controls its spatio-temporal evolution? What governs tsunami generation characteristics for a given great earthquake?

– What are the geologic, physical, and chemical signatures of slow slip, tremor, and seismogenesis? What are the deformation mechanisms recorded in the frontal prism and how do the length scales and timescales of their formation relate to the observed length scales and timescales of strain accumulation and release?

- Does fault state evolve during interseismic and pre-seismic periods? If so, how?

- What do fault zone structure and compositions reveal about slip mechanisms in tsunamigenic frontal ramp thrusts? What are the implications of variable properties for the fault zones and their architecture, evolution, and slip behavior?

- What are the geomechanical, frictional and physical properties of the fault zones and wall rock in the overriding and subducted plate? How do these rock properties vary spatially in the volume of rock away from the borehole, as sampled by 3-D seismic data? How are these properties related to the in situ stress state and strain accumulation?

- What is the ancient and modern thermal state in the frontal prism, and how is it modified by frictional heating and fluid flow?

- What is the porosity and pore fluid pressure evolution in the accretionary prism, basal *décollement*, and under thrust sediments? What are the roles of faults and fractures in fluid circulation within the frontal prism and deformation zones?

- What are the distribution, origin and timing of mass transport deposits and how may these relate to past seismogenic (tsunamigenic) slip, eustacy, and climatic variations?

- What is the sediment provenance of Nankai sediments? What can this tell us about forearc evolution and plate boundary migration over the Miocene to present?

- What is the sequence stratigraphic and tectono-stratigraphic framework of the Kumano basin and forearc? What is the relationship between basin development, uplift, eustasy, or tectonism in the accretionary wedge and trench?

- What is the 3-D spatio-temporal evolution of accretion and fault slip in the frontal prism? How do the timing and rate of slip on prism faults relate to seismogenesis? How does prism evolution respond to changing subduction parameters?

The CLSI@Sea workshop has demonstrated the value of re-investigating archive data. The results arising from post-cruise research undertaken by the participants has the potential to further improve our understanding of the Nankai Trough and subduction processes.

5.3 Lessons learned and suggestions for future workshops

The CLSI@Sea workshop was the first of its kind to run alongside an IODP expedition. The initiative was motivated by a need to re-investigate legacy data, and to bring "new eyes" to the NanTroSEIZE program. Some suggestions arising from this new initiative were the following.

- *Multi-disciplinary collaboration*. One of the keys in the efficacy and the success of the CLSI@Sea workshop was the multi-disciplinarity of the participant pool (Table 1), resulting in a complementary approach to the scientific questions, which demonstrates the value of group collaboration in tandem with individual research projects. Results from studying the evolution of the Nankai Trough highlighted the multi-parameter factors of the complex processes occurring at this plate boundary, and the necessity to address subduction and earthquake mechanisms with multiple methodologies that integrate across different scales of space and time. Similar initiatives on specific research thematics or regional problematics, including data and core material from former IODP expeditions, could represent an efficient mechanism by which research value could be added to the IODP legacy.

- *Communication and focussing*. Connecting specialist mentors and early-career scientists from different backgrounds successfully resulted in a transfer of knowledge between both parties. Lively discussions in a cordial atmosphere and teamwork between mentors, participants and IODP staff in the *Chikyu* focused environment were key components in the development of scientific questions and efficient formulation of both individual and collective research plans. Face-to-face (or "face-to-direct-live-screen") interactions during talks given by the mentors were crucial to confirm the current state-of-the-art and to avoid duplication of efforts. Self-introduction of workshop participants was also a fundamental point to highlight individual research interests and build research teams and collaborations. Pre-workshop communication (mentors–participants, participants–participants, collection of publications and list of available data during the workshop) represents efficiency in identification of research interests, organization of collaborations, and improvement of individual knowledge and research strategy.

- *Data availability and sampling*. Training on data analytical techniques, school sampling and software support provided by scientific staff was crucial to facilitate access to and work on the data. During CLSI@Sea, workshop participants had the opportunity to access public data (IODP archives) and restricted data (3-D seismic reflection data) kindly provided for investigations. A major issue concerning the archived sedimentary cores is the limited amount of data due to the nature of the cores themselves, by definition limited in terms of quantity of available material. Thus, complete missing sections of cores previously already sampled (fault planes particularly) represented important issues to the participants aiming to analyze the sedimentary records of the deformation, as well as for future researchers interested in investigating sedimentary archives theoretically available for the entire scientific community. This issue could be resolved at long term with the development of non-destructive analysis, such as X-ray CT (see Sects. 4.3 and 5.1).

- *Motivation and self-organization.* The motivation, initiative, and self-organization of the workshop participants were essential keys to the program's success. Most of the ideas on the organization of the research aspect of the workshop (see Sect. 3) came from the participants, who were free to organize their research and expose their ideas to the other participants, supported by the staff scientists and the mentors. This freedom allowed the ideas to arise easily from the discussion sessions and individual thinking, and were a fundamental aspect of the success of the CLSI@Sea workshop.

6 Summary

The Nankai Trough is one of the most active plate margins of the planet, and one of the most studied, being the focus of many IODP expeditions and related surveys that collectively acquired a huge quantity of data over the last decades, thus being a key area for the understanding of tsunamigenic earthquakes. The CLSI@Sea workshop demonstrated the value of revisiting IODP archives and integration of different types of data, core, logging and seismic, providing indications of several processes acting on different scales. The success and the productivity of CLSI@Sea thus demonstrated the interest in organizing such a workshop for any scientific discipline. The workshop participants formulated scientific questions to better understand the sedimentary, structural and physical aspects of subduction processes. Analyses initiated onboard *Chikyu* are now continuing at participants' home institutions, following the research plans elaborated during the workshop. CLSI@Sea participants plan to meet in the year following the workshop, in order to discuss and correlate their results, confident that international collaboration will lead to high-impact outcomes in the global understanding of inter-disciplinary processes in subduction zones.

Data availability. All the data used during this workshop and presented in this report are archived IODP data and therefore publicly accessible, or accessible on request, from the IODP website (https://www.iodp.org/resources/access-data-and-samples, IODP Science support office, 2018).

Information about the Supplement

Supplementary movie. Three-dimensional distributions of bulk density converted from the CT value presented in Fig. 6. In Supplement movies, the same section (C0006E31X05 110–128 cm) is rotated horizontally. The color scale is the same as the one presented in Fig. 6.

The Supplement related to this article is available online at: https://doi.org/10.5194/sd-24-93-2018-supplement

Author contributions. RF, BG, GL, TM, CR and SY were the main contributors to this report. All authors participated in the discussions, data synthesis and writing. GL suggested writing and publishing this report and coordinated the writing work during and after the expedition.

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

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All investigators, workshop attendees, the Exp. 380 Science party and daily reports can be found on the NanTroSEIZE Expedition 380 project website at https://www.jamstec.go.jp/chikyu/e/nantroseize/expedition_380.html (last access: 22 September 2018).

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