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Editorial Preface

Dear Reader,

This new issue of your journal Scientific Drilling conveys several changes. In the past, the journal has been edited and produced by the Integrated Ocean Drilling Program through IODP Management International's Tokyo office since 2005. With the start of the new International Ocean Discovery Program, the journal is now organized by the International Continental Scientific Drilling Program from their office in Potsdam, Germany while the publication is in the hands of Copernicus Publications. You will see a few minor changes in the design of the journal to reach out to a broader community and to achieve a larger impact. The open access online version of the journal will play a much bigger role in future and the production of a printed version will be scaled down.

Coming along with the new publication concept of Scientific Drilling, the transition in IODP to a simplified funding model for the major ocean drilling platforms, a streamlined program management structure, and a smaller science advisory structure has been implemented. The IODP Science Plan for 2013–2023, *Illuminating Earth's Past, Present, and Future*, builds on the achievements of the past ten years and presents new challenges. ICDP is about to enter a new era as well starting with the creation of a new Science Plan in November 2013 through a conference to be held in Potsdam under the title Imaging the Past to Imagine our Future.

Nonetheless, scientific drilling is in full swing. IODP Expedition 339 addressed orbital- to millennial scale climate variability at the Shackleton Site (page 13) and the environmental significance of the Mediterranean outflow into the Atlantic Ocean some 5.3 Ma ago (see page 1). Earlier extreme events are the hyperthermals of Eocene and Paleogene times recorded in fluvial deposits in Wyoming that are used in the Bighorn Basin Coring Project to study high-resolution proxy records (page 21). A meeting on the Mochras succession in Wales looked even further back in time to Early Jurassic extreme environmental changes on page 81 and another scientific drilling workshop identified global key locations for paloeobiology, paleoclimatology, stratigraphy and biogeochemistry (page 63) over various time scales.

The development of cutting-edge methods and tools for in-situ sampling and monitoring plays a crucial role in characterizing natural analogues for possible CO_2 storage sites (page 33), in improving our understanding of the serpentine-hosted biosphere through an observatory (page 45) and in instrumenting a sub-seafloor observatory to study dynamic processes (page 57). Plans to approach deep fluid movements causing earthquake swarms in the Eger Rift (Czech Republic) by scientific drilling are presented on page 93 whereas the Iceland Deep Drilling Project heads towards harvesting supercritical black smoker fluids through a 4 to 5 km deep exploratory borehole (page 73).

Your Editors
Ulrich Harms, Thomas Wiersberg, Gilbert Camoin,
James Natland, and Tomoaki Morishita

Aims & Scope

Scientific Drilling (SD) is a multidisciplinary journal focused on bringing the latest science and news from the scientific drilling and related programs to the geosciences community. Scientific Drilling delivers peer-reviewed science reports from recently completed and ongoing international scientific drilling projects. The journal also includes reports on Eng-ineering Developments, Technical Developments, Workshops, Progress Reports, and news and updates from the community.

Editorial Board

Additional Information

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Cover figures: Drillship JOIDES Resolution on IODP expedition 339. Photos: F. J. Hernández-Molina

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IODP Expedition 339 in the Gulf of Cadiz and off West Iberia: decoding the environmental significance of the Mediterranean outflow water and its global influence

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Abstract. IODP Expedition 339 drilled five sites in the Gulf of Cadiz and two off the west Iberian margin (November 2011 to January 2012), and recovered 5.5 km of sediment cores with an average recovery of 86.4 %. The Gulf of Cadiz was targeted for drilling as a key location for the investigation of Mediterranean outflow water (MOW) through the Gibraltar Gateway and its influence on global circulation and climate. It is also a prime area for understanding the effects of tectonic activity on evolution of the Gibraltar Gateway and on margin sedimentation. We penetrated into the Miocene at two different sites and established a strong signal of MOW in the sedimentary record of the Gulf of Cadiz, following the opening of the Gibraltar Gateway. Preliminary results show the initiation of contourite deposition at 4.2–4.5 Ma, although subsequent research will establish whether this dates the onset of MOW. The Pliocene succession, penetrated at four sites, shows low bottom current activity linked with a weak MOW. Significant widespread unconformities, present in all sites but with hiatuses of variable duration, are interpreted as a signal of intensified MOW, coupled with flow confinement. The Quaternary succession shows a much more pronounced phase of contourite drift development, with two periods of MOW intensification separated by a widespread unconformity. Following this, the final phase of drift evolution established the contourite depositional system (CDS) architecture we see today. There is a significant climate control on this evolution of MOW and bottom-current activity. However, from the closure of the Atlantic–Mediterranean gateways in Spain and Morocco just over 6 Ma and the opening of the Gibraltar Gateway at 5.3 Ma, there has been an even stronger tectonic control on margin development, downslope sediment transport and contourite drift evolution. The Gulf of Cadiz is the world's premier contourite laboratory and thus presents an ideal testing ground for the contourite paradigm. Further study of these contourites will allow us to resolve outstanding issues related to depositional processes, drift budgets, and recognition of fossil contourites in the ancient record on shore. The expedition also verified an enormous quantity and extensive distribution of contourite sands that are clean and well sorted. These represent a relatively untapped and important exploration target for potential oil and gas reservoirs.

1 Introduction and goals

Integrated Ocean Drilling Program (IODP) Expedition 339 combined IODP Proposal 644-Full2 and ancillary proposal letter (APL)-763 (see Hodell et al., this issue). The expedition was primarily paleoceanographic in nature, focusing mainly on the broader significance of Mediterranean outflow water (MOW) on North Atlantic Ocean circulation and climate (Expedition 339 Scientists, 2012). This expedition offered a rare opportunity to understand the global link between paleoceanographic, climatic, and sea level changes from Messinian to the present and addressed the importance of ocean gateways in regional and global ocean circulation

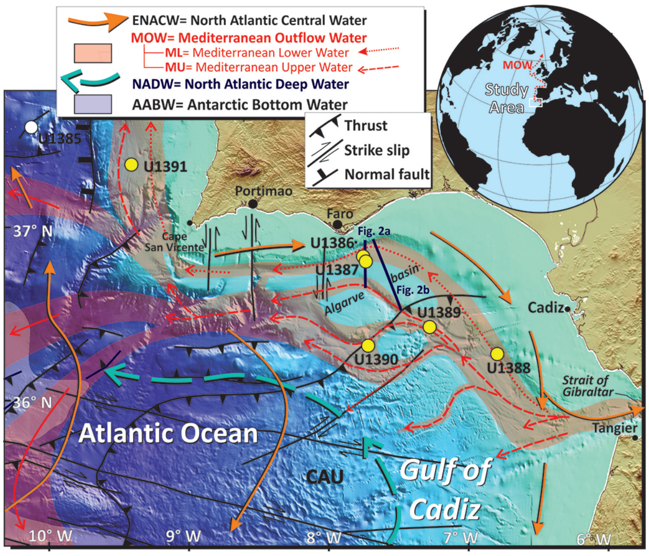

Figure 1. Expedition 339 sites in the Gulf of Cádiz and west Iberian margin, shown as yellow/white solid circles. Bottom water masses and ocean currents shown as NADW = North Atlantic deep water; AABW = Antarctic Bottom Water; ENACW = east North Atlantic common water; MOW = Mediterranean outflow water; MU, ML, AI = Atlantic Inflow.

and climate. Sites related to the Proposal 644-Full2 were specifically located in order to study the contourite depositional system (CDS) generated by the MOW influence in the Gulf of Cádiz and on the west Iberian margin (Fig. 1). In this paper we present a summary of the expedition goals, a regional background to the study area and the main preliminary results of the expedition.

The extensive CDS that has been developing within the Gulf of Cádiz and extending around the west Iberian margin over the past 5 My is a direct result of MOW (e.g., Madelain, 1970; Gonthier et al., 1984; Faugères et al., 1985; Nelson et al., 1993, 1999; Llave et al., 2001, 2006, 2007, 2011; Stow et al., 2002, 2013a; Habgood et al., 2003; Hernández-Molina et al., 2003, 2006, 2011b; Mulder et al., 2003, 2006; Hanquiez et al., 2007; Marchès et al., 2007; Roque et al., 2012; Brackenridge et al., 2013). The high accumulation rates and expanded sedimentary records of drift deposits permit a high-resolution examination of past environmental change (Llave et al., 2006; Voelker et al., 2006). The CDS deposits, therefore, hold the very best signal of MOW flow through the Strait of Gibraltar gateway and a clear record of its influence on the oceanography and climate of the North Atlantic Ocean and on the North Atlantic deep water (NADW) variability (Bigg and Wadley, 2001a, b; Bigg et al., 2003). However, the region had not previously been drilled for scientific purposes, even though the Gibraltar Gateway clearly has major implications for global climate and oceanography.

Expedition 339 was certainly ambitious in scope and scientifically very exciting. It was carefully crafted by a broad spectrum of scientists over at least a 9 yr gestation period. The expedition reflects intense international interest in the region and its global significance, building on a research database accumulated over 35 yr. Furthermore, the study of the CDS should be of great interest to the international community not only because of its stratigraphic, sedimentologic, paleoceanographic, and paleoclimatologic significance but also because of its close relationship with possible specific deep-marine geohabitats and/or mineral and energy resources (Rebesco and Camerlenghi, 2008; Hernández-Molina et al., 2011a). The next principal objectives of Expedition 339 address key elements of the IODP Initial Science Plan (ISP) through targeted drilling of a Neogene and Quaternary continental margin sequence in the Gulf of Cádiz and off West Iberia (Expedition 339 Scientists, 2012): (1) understand the opening of the Strait of Gibraltar as one of the main oceanic gateways worldwide and the onset of MOW; (2) determine MOW paleocirculation and its global climate significance; (3) identify external controls (climate and sea level changes) on sediment architecture; and (4) ascertain synsedimentary neotectonic control on architecture and evolution of the CDS.

2 Geological and oceanographic setting

The southwestern margin of the Iberian Peninsula, at the eastern segment of the Azores–Gibraltar fracture zone, is the location of the diffuse plate boundary between Eurasia (Iberia) and Africa (Nubia). The present plate convergence rate between the African and Eurasia plates in the Gulf of Cádiz area is $\sim 4\,\mathrm{mm\,yr^{-1}}$ (e.g., Stich et al., 2006) with a WNW–ESE oblique convergence and is accommodated through a series of thrusts (Fig. 1) and dextral strike-slip faults (Zitellini et al., 2009). Distinct periods of crustal deformation, fault reactivation, and halokinesis related to the movement between Eurasia and Africa plates (e.g., Maldonado et al., 1999; Gutscher et al., 2002; Medialdea et al., 2004; Zitellini et al., 2009; Duarte et al., 2011, 2013) are known to have controlled the tectonostratigraphic evolution of this part of the Iberian Peninsula. The tectonic structure of this area is a consequence of the distinct phases of rifting since the Late Triassic to the Early Cretaceous related to the opening of the central and North Atlantic basins (Maldonado et al., 1999) and its later deformation during the Cenozoic, especially in the Miocene (Zitellini et al., 2009; Duarte et al., 2011). The Gulf of Cádiz straddles this oblique-convergence zone between the Eurasia and Africa plates, extending from the Gloria fault to the Gibraltar arc, which marks the western front of the Betic–Rif collisional orogen. Since the late Miocene, an oblique compressional regime has been regionally developed simultaneously with the extensional collapse of the Betic–Rif orogenic front, by westward emplacement of a giant chaotic body known as the Cadiz Allochthonous Unit (CAU) (Medialdea et al., 2004, 2009) or Gulf of Cadiz

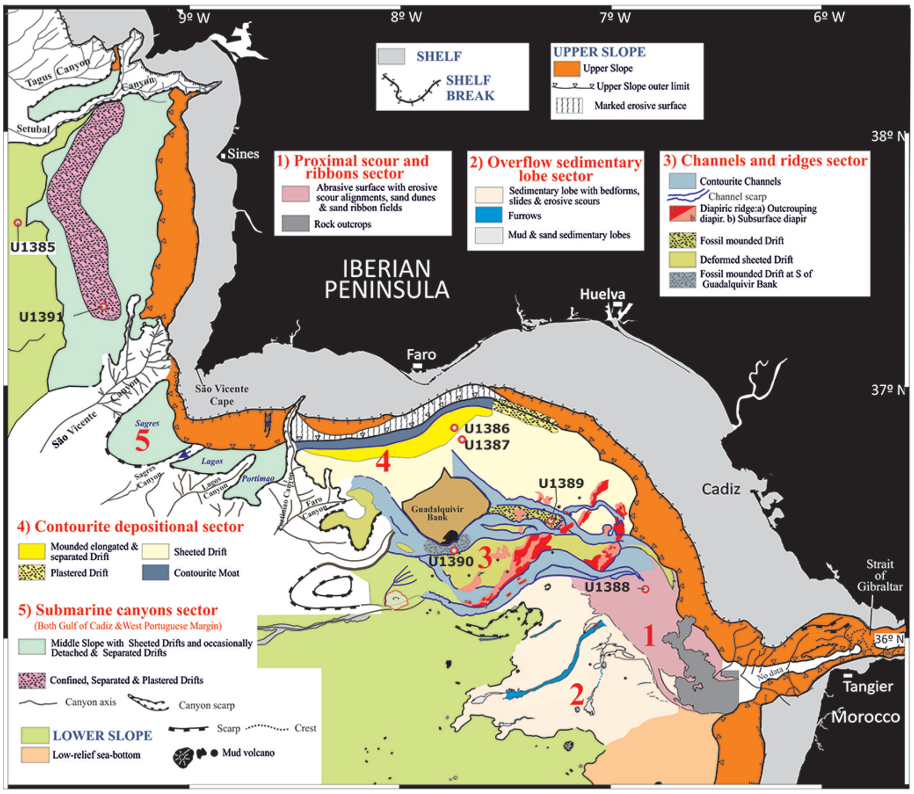

Figure 2. Regional map of the contourite depositional system on the middle slope of the Gulf of Cádiz and west Iberian margin with Expedition 339 site locations. Morphosedimentary sectors (1–5) based on Hernández-Molina et al. (2003, 2006) and S. Lebreiro (personel communication, 2006).

accrecionary prism (Gutscher et al., 2002) (former named "Olistostrome" by Maldonado et al., 1999), and by very high rates of basin subsidence coupled with strong diapiric activity (Maldonado et al., 1999; Alves et al., 2003; Terrinha et al., 2003, 2009; Zitellini et al., 2009; Roque et al., 2012). During the Pliocene and Quaternary, the effect of glacio-eustatic variations have partly overprinted structural effects on the margin and resulted in erosion, sedimentary progradation and incision of major submarine canyons. By the end of the lower Pliocene, subsidence decreased and the margin evolved towards its present more stable conditions (Maldonado et al., 1999; Alves et al., 2003; Medialdea et al., 2004; Llave et al., 2011; Roque et al., 2012). Some neotectonic reactivation is also evident as expressed by the occurrence of mud volcanoes and diapiric ridges, and fault reactivation (Zitellini et al., 2009).

Present-day circulation pattern in the Gulf of Cadiz is dominated by exchange of water masses through the Strait of Gibraltar (Fig. 2). This exchange is driven by the highly saline and warm MOW near the bottom and the turbulent, less saline, cool-water mass of Atlantic water at the surface. Regionally five water masses are identified: surface Atlantic water (SAW); eastern North Atlantic central water (ENACW); modified Antarctic intermediate water (AAIW); MOW; and the NADW (Serra et al., 2010; Rogerson et al., 2012; Louarn and Morin, 2011). MOW forms a strong bottom current flowing toward the west and northwest above NADW. After it exits through the Gibraltar Gateway, MOW represents a flux of ~1.78 Sv of intermediate water mass, which is warm and very saline that flows to the northwest along the middle slope under Atlantic inflow and above NADW generates important along-slope sedimentary processes along the Atlantic margin (see compilation on Hernández-Molina et al., 2011b). In the Gulf of Cádiz, MOW flows between 500 and 1400 m below sea level (m b.s.l.) with a velocity close to 300 cm s^{-1} at the Strait of Gibraltar and ~80–100 cm s^{-1} at the latitude of Cape San Vicente. Its distribution is conditioned by the complex morphology of the continental slope, which generates two main cores (Fig. 2), between 500 and 700 m b.s.l. (upper core or Mediterranean upper water (MUW)) and 800 and 1400 m b.s.l. (lower core or Mediterranean lower water (MLW)). MLW is further divided into three branches. After exiting the Gulf of Cádiz, MOW has three principal branches, but one of them is flowing north around the Iberian margin reaching the Norwegian Sea (Iorga and Lozier, 1999).

The interaction of MOW with the Gulf of Cádiz and west off the coast of Portugal margin has resulted in the

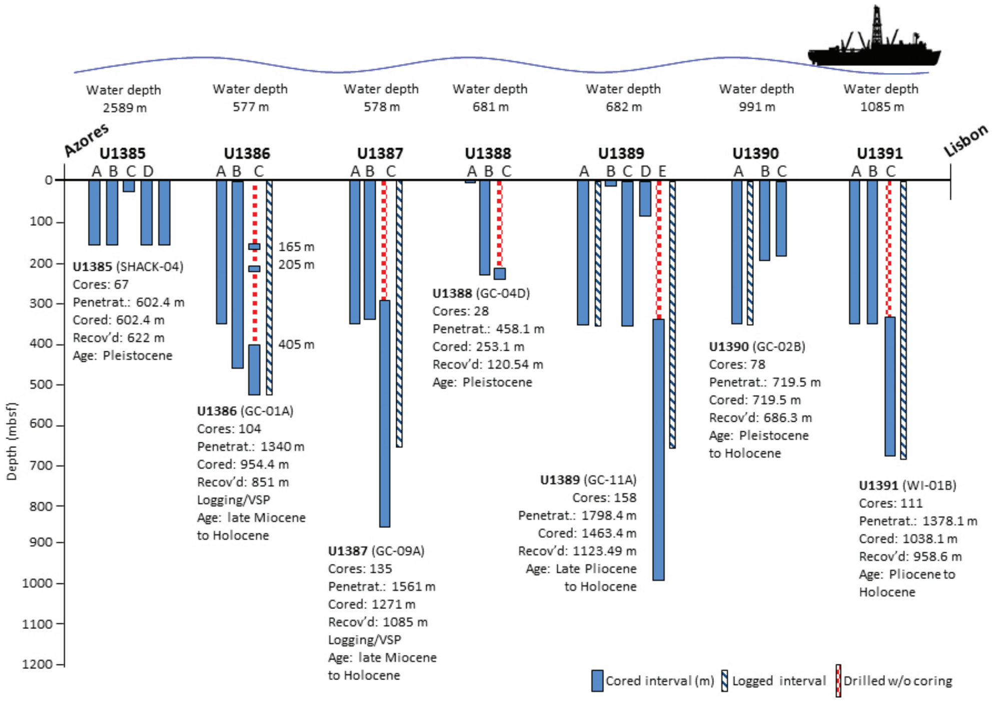

Figure 3. Expedition 339 sites information. 19 holes (681 cores) were drilled on 46.1 days on site, with a penetration of 7857.4 m, cored 6301.6 and recovered 5446.7 m (86.4 %).

development of one of the most extensive and complex CDSs ever described (Fig. 2). Many authors have highlighted this interaction and have characterized its features along the middle slope (e.g., Gonthier et al., 1984; Nelson et al., 1993, 1999; Llave et al., 2001, 2006, 2007, 2011; Habgood et al., 2003; Hernández-Molina et al., 2003, 2006; Mulder et al., 2003, 2006; Hanquiez et al., 2007; Marchès et al., 2007; Roque et al., 2012 among many other). Specific location of large depositional and erosional features within the CDS defines five morphosedimentary sectors (details in Hernández-Molina et al., 2003, 2006), whose development is related to a systematic deceleration of MOW as it flows westward from the Strait of Gibraltar, caused by its interaction with margin bathymetry and the effects of Coriolis force. In general, the drifts are composed mainly of muddy, silty, and sandy sediments, with a mixed terrigenous and biogenic composition (Gonthier et al., 1984). In contrast, sand and gravel are found in the large contourite channels (Nelson et al., 1993, 1999; Stow et al., 2013a), as are many erosional features (Hernández-Molina et al., 2006, 2012). In the proximal sector close to the Strait of Gibraltar, an exceptionally thick (~ 815 m) sandy-sheeted drift occurs, with sand layers averaging 12–15 m thick (Buitrago et al., 2001).

3 Drilling expedition

Expedition 339 drilled five sites in the Gulf of Cádiz (U1386–U1390) and two sites off the west Iberian margin (U1385 and U1391) from 17 November 2011 to 17 January 2012 (http://iodp.tamu.edu, Fig. 1). Six of the sites, U1386–U1391, were specifically selected in order to study the contourite depositional system (CDS) generated by MOW (Fig. 2).

Global Positioning System (GPS) coordinates from precruise site surveys were used to position the vessel at all Expedition 339 sites. A SyQuest Bathy 2010 CHIRP subbottom profiler was used to monitor the seafloor depth at each site to reconfirm the depth profiles from pre-cruise surveys. Once the vessel was positioned at a site, the thrusters were lowered and a positioning beacon was dropped to the seafloor. The dynamic positioning (DP) control of the vessel used navigational input from the GPS system and triangulation to the seafloor beacon, weighted by the estimated positional accuracy. The final hole position was the mean position calculated from the GPS data collected over a significant portion of the time the hole was occupied. A survey of the seafloor was conducted at all sites using the underwater camera system to ensure that it was free of obstructions.

All three standard coring systems – the advanced piston corer (APC), the extended core barrel (XCB), and the rotary core barrel (RCB) – were used during Expedition 339 (Stow et al., 2013b), which allowed us to drill 19 holes (681 cores) onboard the scientific drillship, D/V *JOIDES Resolution* on 46.1 days on site, with a penetration of 7857.4 m, cored 6301.6 m. In total, nearly 5.5 km of core were recovered, with

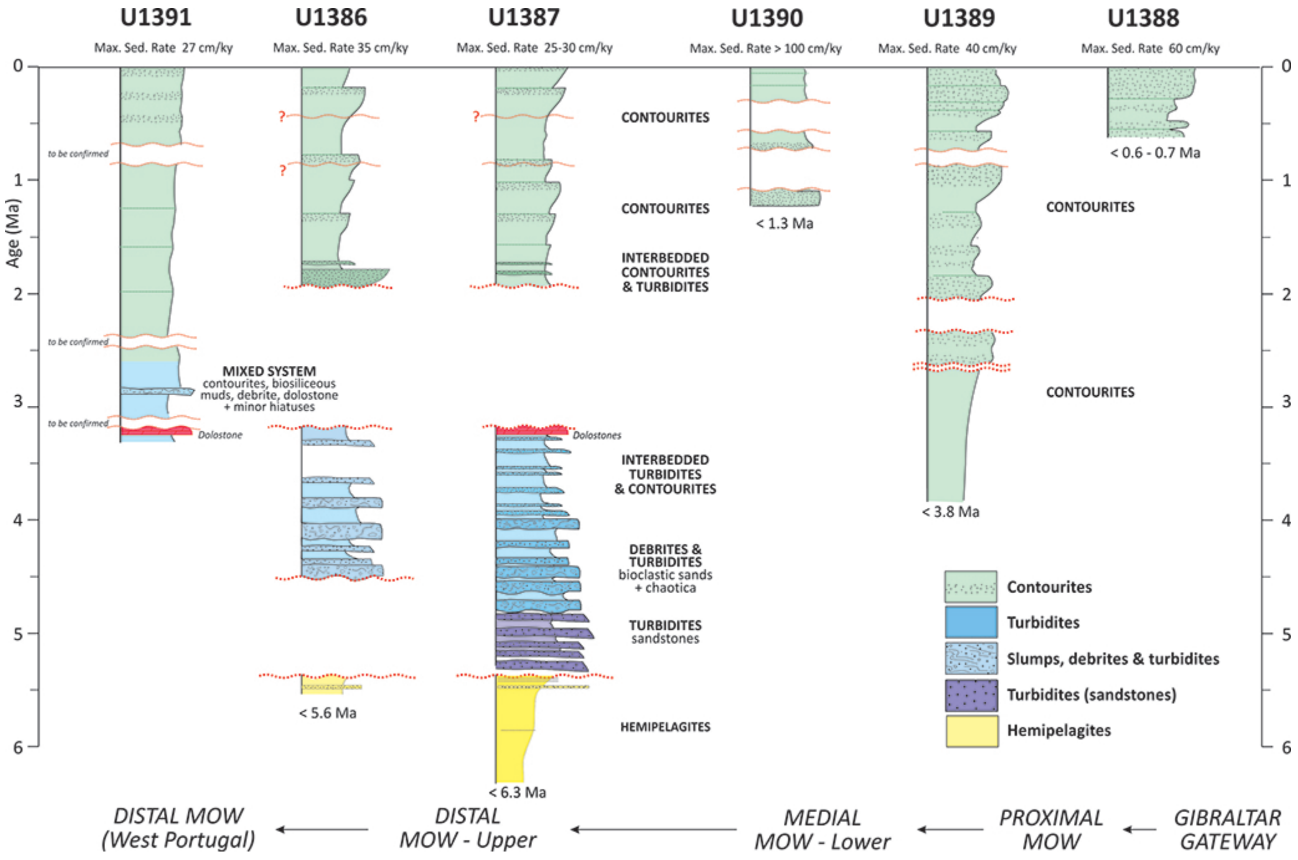

Figure 4. Lithologic summary for the sites drilled during IODP Expedition 339 in the Contourite Depositional System of the Gulf of Cadiz and west off Portugal. A general interpretation, including the position of principal hiatuses, is indicated. Age models are based on biostratigraphic datums and magnetostratigraphy. Sedimentation rates for the Pliocene = 15–25 cm ky^{-1} and for the Quaternary = ~30 to > 100 cm ky^{-1}. Site location on Fig. 1.

an average recovery of 86.4 % (Fig. 3), from a region never before drilled for scientific purposes.

4 Preliminary results

The Gulf of Cádiz represents a key location for the investigation of MOW through the Gibraltar Gateway and its influence on global circulation and climate and is a prime area for understanding the effects of tectonic activity on evolution of the Gibraltar Gateway and on margin sedimentation. The Gulf of Cádiz has also become known as the world's premier contourite laboratory in which to thoroughly investigate and challenge existing models of contourite sedimentation. Extensive previous work, both on shore and offshore and including seismic surveys for oil company exploration, has allowed us to develop a good regional understanding. Most importantly, we have been able to establish a firm seismic stratigraphic framework into which we could fit the ages of key seismic horizons as determined by the drilling results from this expedition.

Shipboard biostratigraphic dating was achieved at all sites on the basis of first and last appearances of key marker species of calcareous nannofossils and planktonic foraminifers, as well as on one benthic foraminiferal datum. There is very close correspondence between biostratigraphic and magnetostratigraphic dating, which has allowed for dating certain important horizons, such as depositional hiatuses and boundaries between stratigraphic periods, and determined the sedimentary rates (Fig. 4). The principal drilled sediment facies present in the late Miocene to the present sedimentary record include pelagites, hemipelagites, contourites, turbidites, debrites and slump deposits (Figs. 4 and 5). Dolomitic mudstone and dolostone are rare facies that occur locally. Hemipelagic sedimentation dominates the late Miocene succession. Detail of these sedimentologic terms and their possible meaning could be found in Pickering et al. (1989), Reading (1996), Einsele (2000), Rebesco and Camerlenghi (2008), Hüneke and Mulder (2011) and Shanmugan (2012). The dominant sediment type at the CDS sites is contouritic, making up the 95 % of the Quaternary and about 50 % of the recovered Pliocene succession. This facies group includes sand-rich, muddy sand, silty mud and mud-rich contourites, all of which were deposited at moderate (20–30 cm ky^{-1}) to very high (> 100 cm ky^{-1}) rates of sedimentation.

The principal results of Expedition 339 can be summarized as follows (Stow et al., 2013b):

1. *Mediterranean outflow water onset and evolution.* We penetrated the Miocene at two different sites (Fig. 4) and established the strong signal of MOW in the sedimentary record of the Gulf of Cádiz following opening of the Gibraltar Gateway at 5.3 Ma. There is evidence for contourite deposition since the beginning of the Pliocene, but a stronger contourite signal begins at around 4.2–4.5 Ma. Nevertheless, even at this stage the MOW was not well developed and the signal is relatively weak. Additional seismic evidence for sheeted drift development exists in the early Pliocene. The contourite signal is also mixed with considerable downslope resedimentation and hiatuses in the record. The Pliocene succession was penetrated at four sites (Fig. 4), all of which show relatively low bottom-current activity linked with a generally weak MOW, with some evidence for a slow increase in activity through the later Pliocene. Significant unconformities are apparent at ~ 3.0–3.2 indicative of enhanced bottom currents related to intensified MOW. In the lower Quaternary an unconformity exists between 2.1–2.4 My to a variable extent at different sites, which represents the principal phase of MOW intensification from ~ 2.4 Ma. Later, the Quaternary succession shows a much more general pronounced phase of contourite deposition and drift development throughout the region (Fig. 4). Although there is some variation between sites, we recognize two periods of current intensification, noted by increased sandy and silty contourites in the sedimentary record. The first is from ~ 2.0 to 0.9 Ma and culminates in a regional hiatus of variable duration (~ 0.7–0.9 My). The second is from 0.9 Ma to the present; this also includes a more locally developed hiatus at ~ 0.4 Ma. Climate is one of the factors controlling this long-term long-period cyclicity in the development of MOW and bottom-current activity.

2. *Tectonic pulse at a plate boundary.* Regionally, there appears to be very strong tectonic control on margin development, downslope sediment transport, and contourite drift evolution. From the occurrence, nature, and disposition of the sedimentary record, as well as from the known timing of closure and opening of the Atlantic–Mediterranean gateways, we recognize a clear signal of this tectonic activity. We have established a clear signal of tectonic pulsing over the past 6 My in this region that has controlled: (a) closure of Atlantic–Mediterranean connections in Spain and Morocco; (b) initial opening of the Strait of Gibraltar gateway and probable subsequent deepening; (c) continental margin instability and episodes of active downslope resedimentation; (d) basin subsidence in the Gulf of Cádiz; (e) local uplift and diapiric intrusion within the basin, and (f) constriction of MOW and development of narrow core bottom currents instead of a broad tabular flow. According to the timing of these different events, we hypothesize an ~ 1 My duration of tectonic pulsing (phases of major tectonic events) with an overprint of larger ~ 2.5 My cycles, but further future investigations will test this idea.

3. *Testing the contourite paradigm.* Of the 5.5 km of core recovered, at least 4.5 km is from the Cádiz CDS, a natural contourite laboratory. This was the ultimate testing ground for the contourite paradigm. In general, we have found the models for contourite deposition to be in very good order. Sedimentation rates ranged from moderate (~ 20 cm k.y.^{-1}) to extremely high (> 100 cm k.y.^{-1}). The contourites recovered are remarkably uniform in composition and textural attributes. They have a noted absence of primary sedimentary structures and an intense continuous bioturbation throughout. They are particularly characterized by bi-gradational sequences from inverse to normal grading with a range of partial sequence types (Fig. 5), as predicted by the models. However, very interesting modifications are required, for example, to the detail of the sand-silt contributions and the role of sediment supply. These are very significant for future use of contourite systems in paleoceanographic studies and in hydrocarbon exploration. We have documented very interesting interactions between contourite and turbidite processes that are completely new and different from the current models.

4. *Paradigm shift for oil exploration.* We have verified an enormous quantity and extensive distribution of contourite sands (and bottom-current-modified turbidite sands), and have begun to establish their detailed characteristics (Fig. 5). Drilling at the proximal site (U1388) managed to penetrate only the uppermost 226 m of what we had interpreted as a very thick sandy contourite drift. Hole instability and collapse of these unconsolidated sands prevented further penetration. At other proximal sites (U1389 and U1390), we also encountered thick contourite sands (as thick as 10 m) within the muddy contourite drifts. These are completely different deep water sands than the turbidite sands that are currently dominant as deep water oil and gas plays and are formed in different depositional settings, have different depositional architectures, and are clean and well sorted. These characteristics would provide good quality potential reservoirs when buried deeply. In addition, the associated contourite muds are very thick, rapidly deposited, and moderately rich in organic carbon (up to 2 wt %). These could provide potential source rocks in the subsurface, as well as suitable seals in stratigraphic

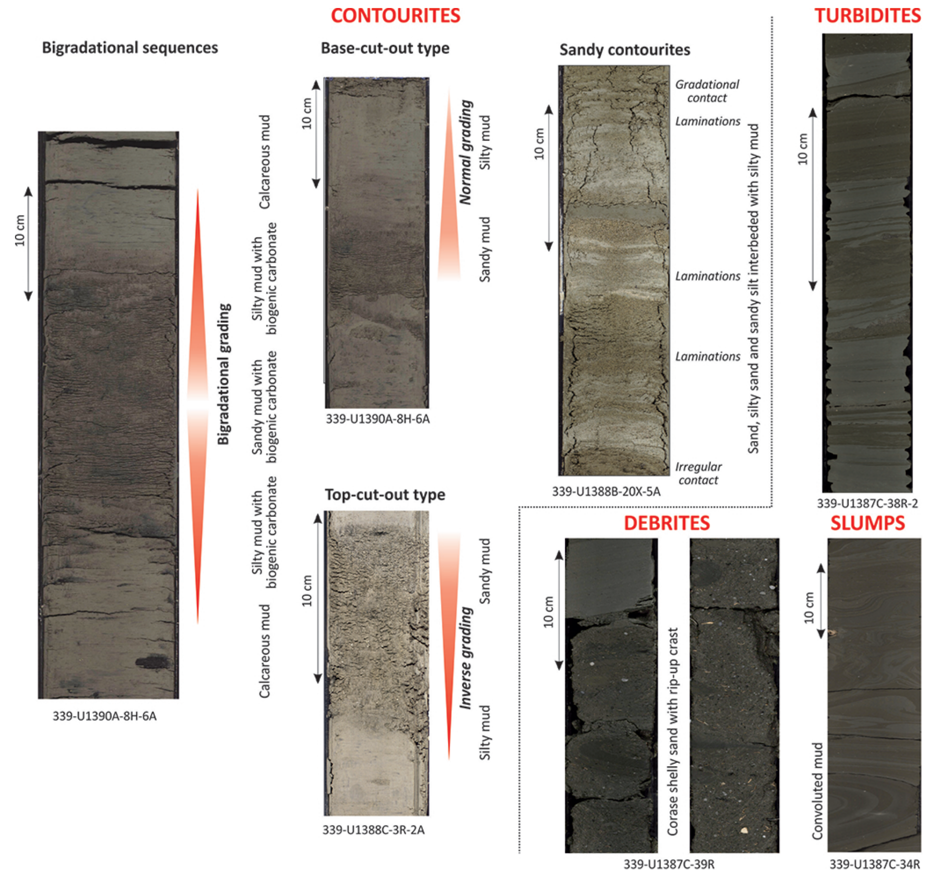

Figure 5. Examples of the principal sedimentary facies for contourites, turbidites, debrites and slumps recovered during IODP Expedition 339.

traps. These new findings could herald a paradigm shift in exploration targets in deep water settings.

5 Expedition synthesis

There can be no doubt that the expedition results have more than met our scientific objectives at the outset. The results are both expected in that they confirm many of our pre-expedition hypotheses, and also unexpected in the wealth of new ideas and data that have arisen. We set out with broad objectives, which have been addressed and met as follows:

- *Understanding of the opening of the Gibraltar Gateway and onset of MOW.* We have drilled to the Miocene at two sites, assessed the basal age of drift sedimentation due to MOW, and evaluated the nature and effects of climate change in the patterns of drift sedimentation. We recognize clear evolution from proximal to distal sites.

- *Determine MOW paleocirculation and global climate significance.* We have penetrated most key Miocene to the present reflectors at one or several sites and have been able to date these reflectors and confirm or refine our seismic stratigraphic framework accordingly. We have been able to understand and evaluate their link to paleocirculation variation and events with respect to MOW, as well as to the sedimentary and tectonic evolution of the whole region. We have recognized orbital and millennial-scale signals in the sedimentary record, which will be evaluated through subsequent work.

- *Identify external controls on sediment architecture of the Gulf of Cadiz and Iberian margin.* We have established the nature of sedimentation and timing of associated hiatuses by drilling and correlation between sites. This has enabled us to further refine our understanding of the stacking pattern and evolution of the Quaternary drift deposits, and to evaluate the nature of contourite cyclicity at different scales. Further detailed work on the contourite sediments will allow us to better understand the nature of the bottom current processes, contourite deposition and gain better insight into the sedimentary budget for contourite drifts. We have already established the key sources of sediment and their controls.

- *Ascertain synsedimentary tectonic control on architecture and evolution of the CDS.* There is a significant climate control on this evolution of MOW and

Figure 6. IODP Expedition 339 Scientists (Credit: John Beck, IODP/TAMU).

bottom-current activity. However, from the closure of the Atlantic–Mediterranean gateways in Spain and Morocco just over 6 Ma and the opening of the Gibraltar Gateway at 5.3 Ma, there has been an even stronger tectonic control on margin development, downslope sediment transport and contourite drift evolution. Based on the timing of events recorded in the sedimentary record, we propose a tectonic pulsing in the region, linked with asthenosphere activity. We have been able to accurately chart the chronology of neotectonic activity in the Gulf of Cadiz and to clearly see evidence of the varied effects that this activity has had, both on the alongslope (contourite) depositional system and on the downslope component. The timing and local effects of diapiric activity have been established; further work will allow closer refinement and understanding of these effects and of rates of movement.

6 Final considerations and post-expedition plans

The Gulf of Cadiz is the world's premier contourite laboratory and thus presented an ideal testing ground for the contourite paradigm. Following examination of over 4.5 km of contourite cores, the existing models for contourite deposition are found to be in good working order. Their further study will allow us to resolve outstanding issues of depositional processes, drift budgets, and recognition of fossil contourites in the ancient records on shore. The expedition also verified an enormous quantity and extensive distribution of contourite sands that are clean and well sorted. These represent a completely new and important exploration target for potential oil and gas reservoirs (e.g., Viana and Rebesco, 2007; Viana, 2008; Stow and Faugùeres, 2008; Shanmugan, 2006, 2012, 2013; Brackenridge et al., 2013; Stow et al., 2013a). Preliminary work has shown a remarkable record of orbital-scale variation in bulk sediment properties of contourites at several of the drift sites and a good correlation between all sites. The tectonic and climate control on contourite sedimentation is clearly significant at long and middle scale, but further work will determine the nature of controls at the short scale (millennial scale).

After the expedition, the first post-cruise meeting was in April 2012 (College Station, USA) and the sampling party in June 2012 (Bremen, Germany). Currently, therefore, the IODP Expedition 339 scientists are working in more detail combining sample analyses, geophysical and well data to decode the ancient deposits and processes related to the MOW circulation. Results will be presented in the second post-cruise meeting in Tarifa (Cádiz, Spain), in June 2014. In parallel, two international actions are being planned related to the IODP-339: (a) "Deep-water Circulation: Processes and Product" in September 2014 at *Renard Centre of Marine Geology*, Ghent University (Belgium); and (b) a collaboration is being established with the MEDGATE Network (EU-funded Marie Curie Initial Training Network) for reconstructing Mediterranean-Atlantic exchange (http://www.eu-medgate.net) for organizing a meeting between 5–8 May 2015 in Rabat (Morocco).

7 The IODP Expedition 339 scientific party

Co-chiefs of the Expedition-339 are Dorrik Stow, (ECOSSE, Heriot-Watt Univ., UK) and F. Javier Hernández-Molina (Royal Holloway University of London, UK), and the USIO Expedition Project Manager is Carlos Alvarez Zarikian (Texas A&M University, USA). Thirty-four members form the scientific party (http://iodp.tamu.edu/scienceops/precruise/medoutflow/participants.html), which belong to 13 countries and four continents (Fig. 6): Europe (14 researchers); USA (11); Japan (6); Australia (1); Korea (1); China (1) and India (1). In Europe researchers come from Spain (4); UK (2); France (3); Portugal (2); Germany (1); the Netherlands (1); and Austria (1). They cover different research specialities including wireline logging; sedimentology; stratigraphic correlation; sediment physical properties; geochemisty, micropaleontology; and people for outreach and education.

IODP Expedition 339 Scientists

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Scientific Drilling
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The "Shackleton Site" (IODP Site U1385) on the Iberian Margin

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Abstract. Nick Shackleton's research on piston cores from the Iberian margin highlighted the importance of this region for providing high-fidelity records of millennial-scale climate variability, and for correlating climate events from the marine environment to polar ice cores and European terrestrial sequences. During the Integrated Ocean Drilling Program (IODP) Expedition 339, we sought to extend the Iberian margin sediment record by drilling with the D/V *JOIDES Resolution*. Five holes were cored at Site U1385 using the advanced piston corer (APC) system to a maximum depth of ~ 155.9 m below sea floor (m b.s.f.). Immediately after the expedition, cores from all holes were analyzed by core scanning X-ray fluorescence (XRF) at 1 cm spatial resolution. Ca/Ti data were used to accurately correlate from hole-to-hole and construct a composite spliced section, containing no gaps or disturbed intervals to 166.5 m composite depth (mcd). A low-resolution (20 cm sample spacing) oxygen isotope record confirms that Site U1385 contains a continuous record of hemipelagic sedimentation from the Holocene to 1.43 Ma (Marine Isotope Stage 46). The sediment profile at Site U1385 extends across the middle Pleistocene transition (MPT) with sedimentation rates averaging ~ 10 cm kyr^{-1}. Strong precession cycles in colour and elemental XRF signals provide a powerful tool for developing an orbitally tuned reference timescale. Site U1385 is likely to become an important type section for marine–ice–terrestrial core correlations and the study of orbital- and millennial-scale climate variability.

1 Introduction

Few marine sediment cores have played such a pivotal role in paleoclimate research as those from the southwestern Iberian margin (Fig. 1; hereafter referred to as the "Shackleton sites"). Nick Shackleton's original interest in the Iberian margin was to correlate marine sediment cores with European pollen stratigraphies, but the unexpected correlation of core MD95-2042 to the polar ice cores proved to be an exceptional windfall. Shackleton et al. (2000, 2004) showed that the planktic oxygen isotopic record could be correlated precisely to temperature variations (i.e. δ^{18}O) in Greenland ice cores, especially during MIS3 (Fig. 2). By comparison, the benthic δ^{18}O signal in the same cores resembles the temperature record from Antarctica. Moreover, the narrow continental shelf and proximity of the Tagus River results in the rapid delivery of terrestrial material, including pollen, to the deep-sea environment, thereby permitting direct correlation to European terrestrial sequences (e.g. Sánchez-Goñi et al., 1999; Shackleton et al., 2003; Tzedakis et al., 2004, 2009). Few places exist in the world ocean where such detailed and unambiguous marine–ice–terrestrial correlations are possible.

In November 2009, an ECORD-sponsored Magellan workshop was held in Lisbon, Portugal, to develop plans for

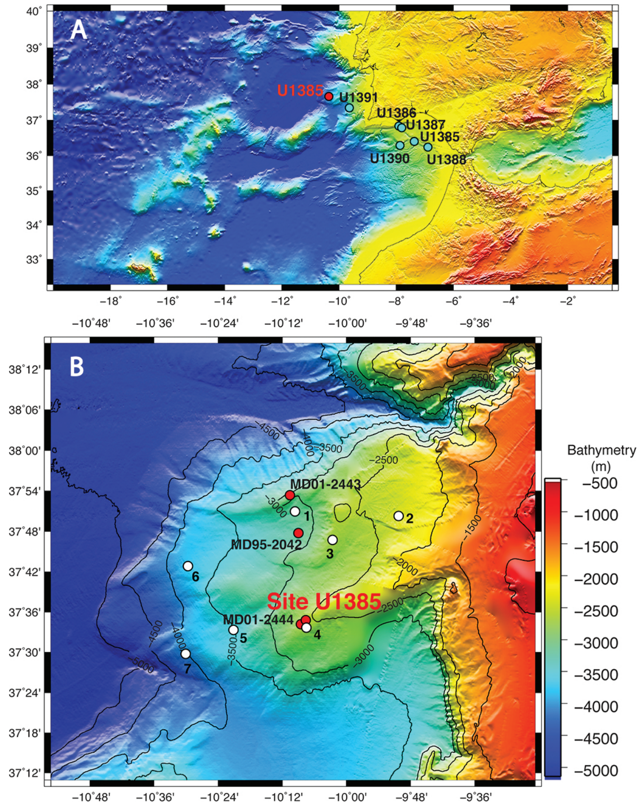

Figure 1. Maps of **(A)** west Iberian margin showing the location of sites drilled during the IODP Expedition 339 **(B)** Detailed bathymetry (Zitellini et al., 2009) of the Promonotorio dos Principes de Avis, including the locations of selected *Marion Dufresne* (MD) piston cores, the IODP Site U1385 (37°34.285′ N, 10°7.562′ W; 2578 m b.s.l.), and proposed drilling site in the proposal IODP 771-Full. Modified after Expedition 339 Scientists (2013b).

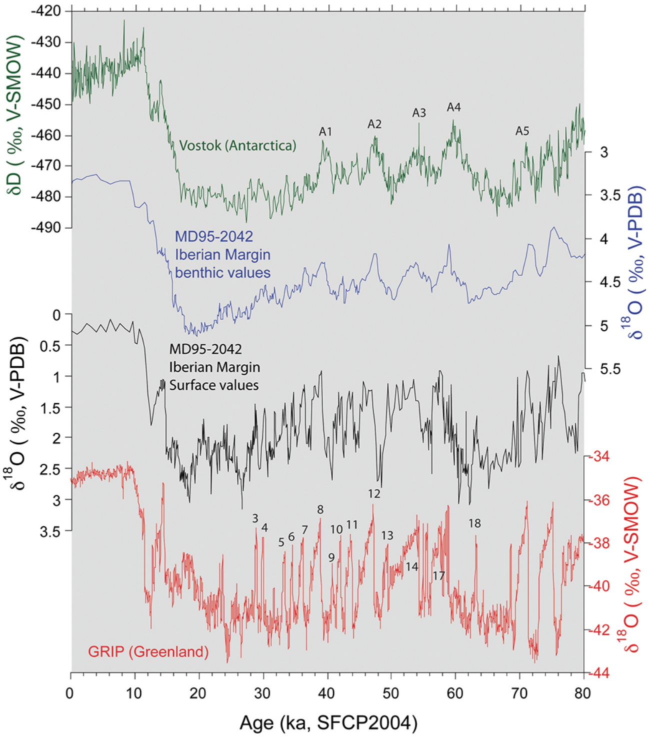

Figure 2. Correlation of δ^{18}O record of Greenland ice core (red) to δ^{18}O of *Globigerina bulloides* (black) in Core MD95-2042 (Shackleton et al., 2000). Resulting correlation of Vostok δD (green) and benthic δ^{18}O of Core MD95-2042 (blue) is based on methane synchronization. VPDB = Vienna Peedee belemnite, VSMOW = Vienna standard mean ocean water. Modified after Expedition 339 Scientists (2013a).

obtaining a long sediment record from the Iberian margin (Abrantes et al., 2010). A full proposal (771-Full) and Ancillary Program Letter (APL 763) were submitted to the Integrated Ocean Drilling Program (IODP), with the latter requesting four days of ship time to drill one of the “Shackleton sites” to 150 m b.s.f. APL-763 was approved for drilling and scheduled as part of the IODP Expedition 339, whose main purpose was to study the history of Mediterranean Outflow Water (see Hernández-Molina et al., this issue).

2 Recovery

IODP Site U1385 (37°34.285′ N, 10°7.562′ W) was drilled in November 2011 (Fig. 1). The site is located on a spur, the Promonotorio dos Principes de Avis, along the continental slope of the southwestern Iberian margin, which is elevated above the abyssal plain and influence of turbidites. The site is near the position of piston core MD01-2444, which has provided a remarkable record of millennial-scale climate variability of the last 190 ka (Vautravers and Shackleton, 2006; Skinner et al., 2007; Margari et al., 2010; Martrat et al., 2007; Hodell et al., 2013). The water depth (2578 m b.s.l.) of Site U1385 places it under the influence of Northeast Atlantic Deep Water today, although it was influenced by southern-sourced waters during glacial periods.

Five holes were cored at Site U1385 using the advanced piston corer (APC) system to a maximum depth of ~ 155.9 m b.s.f. A total of 67 cores were recovered representing 621.8 m of sediment with a nominal recovery of 103.2 % (> 100 % due to post-recovery core expansion). The sediment lithology consists of uniform, nannofossil muds and clays, with varying proportions of biogenic carbonate and terrigenous sediment (Expedition 339 Scientists, 2013a).

Following the cruise, split cores from all holes were analyzed by core scanning X-ray fluorescence (XRF) at the University of Cambridge and the Royal Netherlands Institute for Sea Research (NIOZ) to obtain semi-quantitative elemental data at 1 cm spatial resolution (Fig. 3). These data were used to accurately correlate among holes and construct a complete spliced stratigraphic section, containing no notable gaps or disturbed intervals to 166.5 mcd.

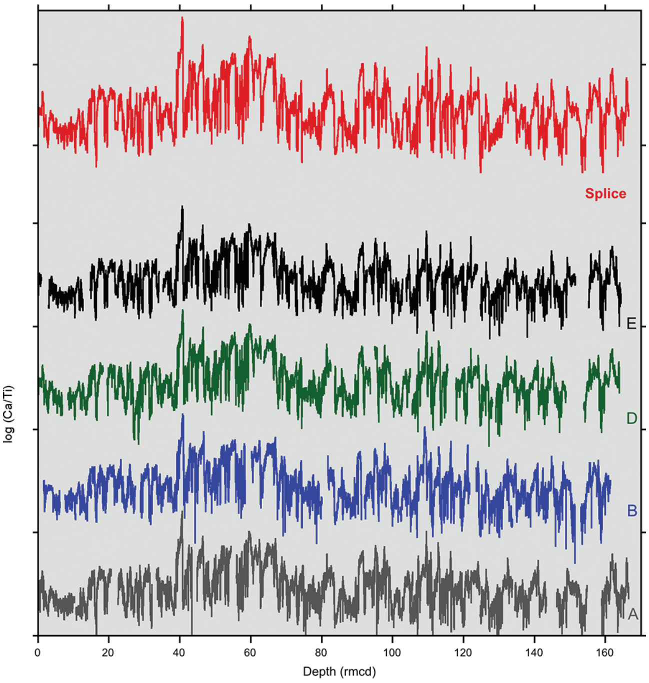

Figure 3. Log Ca/Ti measured by scanning XRF in Holes A (grey), B (blue), D (green), and E (black) from Site U1385. The spliced Ca/Ti record (red) is comprised of segments from Holes A, B, D, and E. Ca/Ti is a proxy for weight %$CaCO_3$ content and reflects the relative proportion of biogenic carbonate and detrital sediment (Hodell et al., 2013).

3 Developing an accurate chronology

A pre-requisite for all future paleoclimatic studies utilizing Site U1385 will be developing an accurate timescale. A low-resolution (20 cm) benthic oxygen isotope record (Fig. 4) demonstrates that Site U1385 contains a complete record from the Holocene to 1.43 Ma (Marine Isotope Stage 46). The record can be correlated unambiguously to the LR04 benthic δ^{18}O stack (Lisiecki and Raymo, 2005) to provide an initial age model. Variations in sediment colour contain very strong precession signals at Site U1385 (Fig. 5), which will be used for orbital tuning.

For the last 800 kyr, it may also be possible to fine-tune the chronology by correlation of millennial events to ice core and speleothem records. The Ca/Ti signal at Site U1385 displays fine-scale millennial variations that mirror planktic δ^{18}O and are highly correlated with alkenone-based sea surface temperature (SST) estimates (Fig. 6). As Shackleton et al. (2000, 2004) demonstrated, these variations could be correlated to the Greenland ice core record. Similarly, Chinese speleothem records also contain millennial-scale “weak monsoon events” that have been correlated to cold phases in the North Atlantic (Cheng et al., 2009). A potential approach for further refining the absolute timescale of Site U1385 will be to correlate the prominent minima in Ca/Ti (corresponding to severe cold events) to weak monsoon events in the speleothem records (Hodell et al., 2013). For the last 800 ka, a “synthetic Greenland” record has been produced by extracting and differentiating the high-frequency variability from the Antarctic EPICA-Dome C ice core record (Barker et al., 2011). Ca/Ti shows a good match with the real and synthetic Greenland ice core δ^{18}O record for the last 120 kyr (Fig. 6), and this correlation could be exploited for fine-tuning the Site U1385 over the past 800 kyr.

4 A marine sediment analog to the polar ice cores

The polar ice cores have provided unrivaled records of climate change that have become benchmarks for Pleistocene climate variability; however, the oldest continuous ice cores recovered to date in Greenland and Antarctica is ~ 124 and 800 ka, respectively. An important challenge is to identify complementary marine sections with sufficiently high sedimentation rates and climate signals suitable for comparison with the polar ice core records. If we assume the correlation between rapid temperature changes on the Iberian margin and over Greenland has held for older glacial periods, then a long millennially resolved record from Site U1385 might serve as a marine sediment proxy record for the Greenland ice core beyond the age of the oldest undisturbed ice (~ 124 ka). Comparing surface water signals at Site U1385 with the synthetic Greenland reconstruction (Barker et al., 2011) and methane record from Antarctica (Loulergue et al., 2008) will test the strengths and weaknesses of using these records as proxies for Greenland temperature change. Similarly, millennial-scale variability in benthic δ^{18}O at Site U1385 will be compared to EPICA δD to determine if the correlation observed for the last glacial cycle holds for the last 800 kyr.

5 Co-evolution of orbital and suborbital climate variability

Although much progress has been made towards understanding the orbital effects on climate, a complete theory of the ice ages still remains elusive (Raymo and Huybers, 2008). A missing piece of the puzzle may be understanding how climate change on shorter timescales (i.e. suborbital) interact with the effects of orbital forcing to produce the observed patterns of glacial–interglacial cycles through the Pleistocene. For example, millennial-scale climatic perturbations may play an important role in longer-term climate transitions, such as glacial terminations (Wolff et al., 2009; Cheng et al., 2009; Denton et al., 2010). Studying the co-evolution of orbital and suborbital variability requires a new calibre of sediment archive with a high level of chronological precision. Our objective is to develop Site U1385 into such a marine reference section for studying the interaction

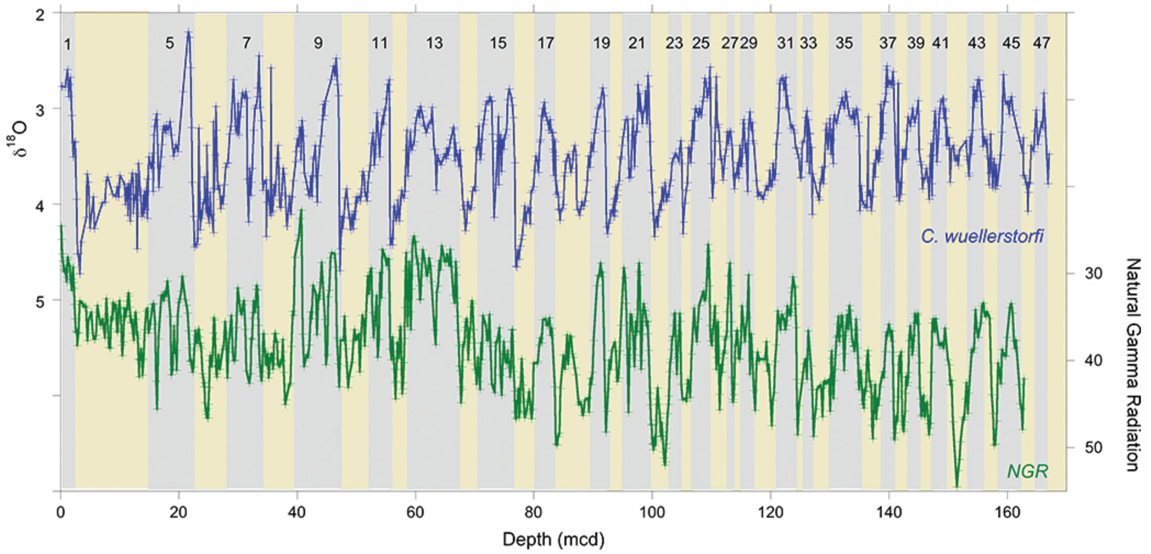

Figure 4. Benthic oxygen isotope record of *Cibicidoides wuellerstorfi* (blue) and natural gamma radiation (green) with identification of marine isotope stages at Site U1385.

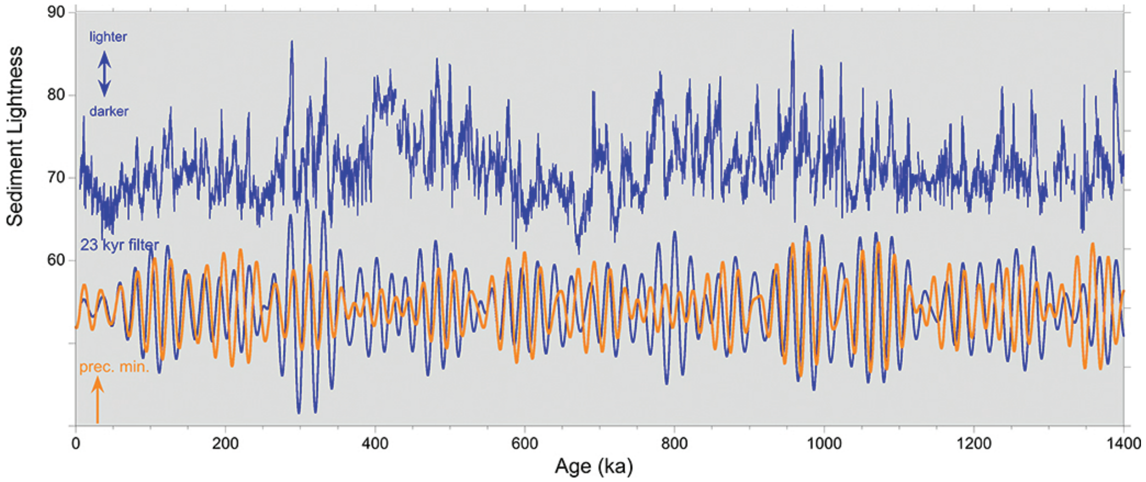

Figure 5. Variations in sediment lightness (L^*) at Site U1385. The 23 kyr filtered signal of lightness (blue) compared to the precession index ($e \times \sin(\omega)$; orange). The potential exists for tuning colour variations at Site U1385 to orbital precession.

of millennial- and orbital- scale climate variability, and for comparing marine, ice, and terrestrial records.

6 Middle Pleistocene transition

The Site U1385 sediment record extends across the middle Pleistocene transition when the climate system evolved from a more linear response to insolation forcing in the "41 kyr world" to one that was decidedly non-linear in the "100 kyr world" (Imbrie et al., 1992). Smaller ice sheets in the 41 kyr world gave way to larger ice sheets in the late Pleistocene with an accompanying change in ice sheet dynamics (Clark et al., 2006; Hodell et al., 2008). Ice volume surpassed a critical threshold across the MPT that permitted ice sheets to survive boreal summer insolation maxima, thereby lengthening glacial cycles and activating the dynamical processes responsible for Laurentide Ice Sheet instability in the region of Hudson Strait (i.e. Heinrich events) (Hodell et al., 2008).

Site U1385 provides an opportunity to examine how millennial-scale climate variability evolved across the MPT as glacial boundary conditions changed. Raymo et al. (1998) provided clear evidence from Site 983 in the North Atlantic that millennial-scale variability was a persistent feature during some glacial periods during the "41 kyr world". Did the nature, timing and frequency of millennial-scale climate variability differ for the "41 kyr world" versus the "100 kyr world"? What are the implications for fresh-water forcing and Atlantic meridional overturning circulation (AMOC)?

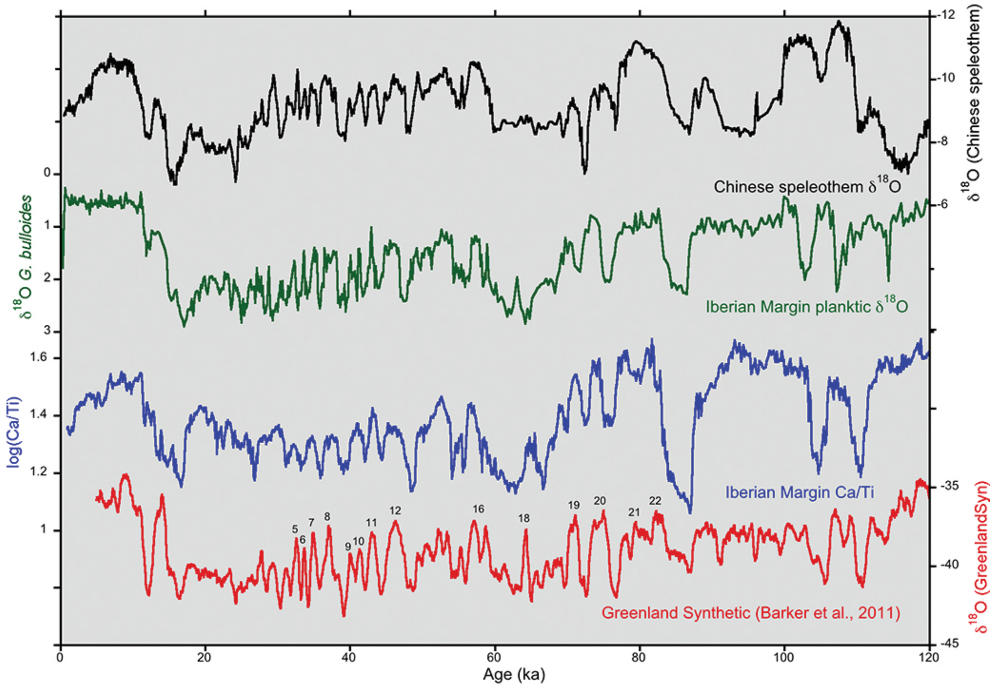

Figure 6. Comparison of Ca/Ti (blue) and planktic δ^{18}O (green) from piston core MD01-2444 (same location as Site U1385) with the Greenland synthetic δ^{18}O record (Barker et al., 2011) and a composite of Chinese spelothem records. The similarity of some of the millennial-scale events offer the opportunity of synchronizing the records and transferring the U-Th-dated chronology of the speleothem record to the ice core and marine sediment archives. Figure reproduced with permission from the American Geophysical Union (Hodell et al., 2013).

7 Testing the bipolar seesaw in glacial periods

The leading cause to explain millennial climate variability recorded in Greenland and Antarctic ice cores during the last glacial period is changes in the strength of AMOC, which alters interhemispheric heat transport and results in opposite temperature responses in the two hemispheres. However, we know little about whether this “bipolar seesaw” was a persistent feature of older glacial periods. A great strength of the Iberian margin sediment record is the fact that it contains signals of both Greenland and Antarctic ice cores in a single archive. Shackleton et al. (2000, 2004) demonstrated it is possible to determine the relative phasing of changes in Greenland and Antarctic climate by comparing planktic and benthic δ^{18}O signals in Core MD95-2042 (Shackleton et al., 2000, 2004). This phasing of surface and deep-water signals on the Iberian margin is consistent with the bipolar seesaw; moreover, millennial-scale warmings in Antarctica preceded the onset of Greenland warmings and the onset of rapid warming in Greenland coincided with cooling in Antarctica. Site U1385 can be used to test if similar phasing existed in older glacial periods, consistent with the operation of a bipolar-seesaw (e.g. Margari et al., 2010). Determining the phase relationships of signals in a single core circumvent many of the problems associated with core-to-core correlation and developing age models that are accurate on millennial timescales.

8 Linking marine and European terrestrial sequences

Marine archives recovered adjacent to the continents have the potential to link continental and marine climate records as they are affected directly by continental inputs, such as sediment from rivers and winds. The western Iberian margin has emerged as a critical area for studying continent–ocean connections because of the combined effects of major river systems and a narrow continental shelf that lead to the rapid delivery of terrestrial material (e.g. pollen, organic biomarkers) to the deep-sea environment (Sánchez Goñi et al., 2000; Shackleton et al., 2003; Tzedakis et al., 2004, 2009; Margari et al., 2010). By comparing marine stable isotopes and pollen records in the same core, the relative timing of land–sea climate change can be determined. Palynological studies of Site U1385 will evaluate how major vegetation changes in southern Europe over the last 1.43 Ma related to changes in global climate as expressed in the marine oxygen isotope record. Site U1385 provides the material needed to significantly improve the precision to which marine climate records can be linked to European terrestrial sequences.

9 Sampling strategy and multi-proxy studies

Two nearly complete secondary splices were constructed, one using intervals from Holes U1385A and U1385B (the

“AB splice”) and the other using intervals from Holes U1385D and U1385E (the “DE splice”). The Ca/Ti data permits precise correlation among the holes to within a few centimeters. We have undertaken a highly coordinated sampling effort of Site U1385 cores to produce the widest range of proxy measurements possible on the same set of samples. With an average sedimentation rate of 10 cm kyr^{-1}, we sampled the composite section of Site U1385 at 1 cm intervals to resolve millennial climate events. With Site U1385, we aim to accept the challenge posed by Alley (2003) that “paleoceanographers should consider following the ice-core community’s lead and organise a research effort to generate a few internationally coordinated, multiply replicated, multiparameter, high time resolution-type sections of oceanic change.”

10 Future drilling

Site U1385 demonstrates the great promise of the Iberian margin to yield long records of millennial-scale climate change and land–sea comparisons. Site U1385 was the fulfillment of APL-763, but a Full Proposal (771) is pending with the IODP for a complete 56-day expedition to the Iberian margin. Drilling additional sites will allow us to both extend the record beyond the base of Site U1385 (1.43 Ma) and recover a full depth transect of sites spanning a range of subsurface water masses. Together with Expedition 339 sites drilled at intermediate water depths (from 560 to 1073 m), the sites would constitute the most complete depth transect drilled on any continental margin. Surface signals are expected to be similar among sites and can be used for site-to-site correlation, whereas benthic signals will reflect the range of subsurface water mass properties. Building on the success of Site U1385 and given the seminal importance of the Iberian margin for paleoclimatology and marine–ice–terrestrial correlations, additional drilling of this region by the IODP is warranted.

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Scientific Drilling
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Bighorn Basin Coring Project (BBCP): a continental perspective on early Paleogene hyperthermals

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Abstract. During the summer of 2011, the Bighorn Basin Coring Project (BBCP) recovered over 900 m of overlapping core from 3 different sites in late Paleocene to early Eocene fluvial deposits of northwestern Wyoming. BBCP cores are being used to develop high-resolution proxy records of the Paleocene–Eocene Thermal Maximum (PETM) and Eocene Thermal Maximum 2 (ETM2) hyperthermal events. These events are short-term, large magnitude global warming events associated with extreme perturbations to the earth's carbon cycle. Although the PETM and ETM2 occurred ~ 55–52 million years ago, they are analogous in many ways to modern anthropogenic changes to the carbon cycle. By applying various sedimentological, geochemical, and palynological methods to the cores, we hope to better understand what caused these events, study the biogeochemical and ecological feedbacks that operated during them, and reveal precisely how they impacted continental environments.

Core recovery was > 98 % in all holes and most drilling was carried out without fluid additives, showing that continuous coring of continental smectitic deposits like these can be achieved with minimal risk of contamination to molecular biomarkers. Cores were processed in the Bremen Core Repository where the science team convened for 17 days to carry out data collection and sampling protocols similar to IODP projects. Initial results show that the weathered horizon extends to as much as ~ 30 m below the surface and variations in magnetic susceptibility within the cores record an interplay between grain size and pedogenesis. Previous investigations of outcrops near the BBCP drill sites allow detailed evaluation of the effects of weathering on common proxy methods. Studies of lithofacies, organic geochemistry, stable isotope geochemistry, calibrated XRF core scanning, paleomagnetics, and palynology are underway and will represent the highest resolution and most integrated proxy records of the PETM from a continental setting yet known. An extensive outreach program is in place to capitalize on the educational value associated with the Bighorn Basin's unusually complete record of Phanerozoic earth history.

1 Background and motivation

The early Paleogene was a particularly dynamic period of earth history. It began with the physical and biological events surrounding the K/Pg boundary (i.e., bolide impact, mass extinction) and progressed into an unusually warm climate state, where global mean annual temperatures were as much as 10 °C higher than today and CO_2 concentrations may have been >1000 ppm. Superimposed on these long-term changes were a series of short-term, potentially orbitally paced, extreme global warming events known as “hyperthermals”. The Paleocene–Eocene Thermal Maximum (PETM), the largest magnitude and best studied hyperthermal, is characterized by a global temperature rise of 5–9 °C in less than 10 kyr and an input of up to 4500 Gt of carbon into the mixed ocean–atmosphere carbon pool (Thomas et al., 2002; Wing et al., 2005; Zachos et al., 2005; Sluijs et al., 2006). The PETM lasted $\sim 170\,000$ yr and is associated with major changes to atmospheric moisture transport, restructuring of global ocean circulation, triggering of high-latitude intercontinental mammalian dispersal, extinction of 35–50 % of deep-sea benthic foraminifera species, mammalian dwarfing, and significant poleward range extensions of continental floras (see reviews by Bowen et al., 2006; Gingerich, 2006; Sluijs et al., 2007; McInerney and Wing, 2011). Although the PETM represents one of the most profound perturbations to the earth system in the last 100 million years, its cause remains unknown with several competing hypotheses being debated. Recent focus of this interval by the deep-sea coring community has established the existence of other, smaller amplitude, carbon cycle perturbations during the Paleogene that mimic the PETM (Thomas and Zachos, 2000; Lourens et al., 2005; Thomas et al., 2006; Agnini et al., 2009; Sexton et al., 2011). These other hyperthermals suggest that the PETM was not a unique event and that short-term, high-amplitude changes to the carbon cycle may be part of natural earth-system variability during greenhouse periods like the early Paleogene.

Understanding the causes and effects of these hyperthermals is particularly important for gaining perspective on the response of the earth system to current anthropogenic changes to the carbon cycle. For instance, the amount of carbon release at the PETM is roughly similar to what is projected for anthropogenic fossil fuel release (Zeebe and Zachos, 2013). However, unlike modern climate change that is just beginning, we can study what happened before, during, and after the PETM. Having a natural analog to the Anthropocene is valuable for informing predictions of future climate change and teaching the public about the dynamic and coupled processes that comprise the earth system. It is also possible that current global warming could trigger a hyperthermal-like feedback not currently accounted for in global climate models, which means that current predictions for future climate change may be substantially underestimated.

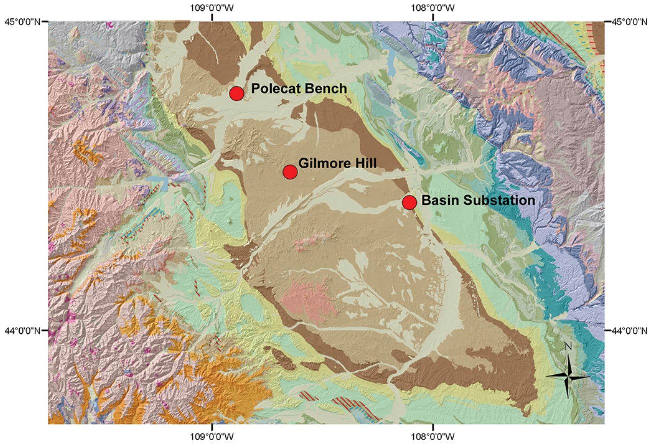

Figure 1. Geological map of Bighorn Basin, Wyoming, showing location of the drill sites associated with the BBCP. Dark brown represents the upper Paleocene Fort Union Formation and light brown represents the lower Eocene Willwood Formation which are the units drilled during the BBCP.

We undertook a targeted scientific drilling project in the Bighorn Basin, Wyoming, to recover continuous continental sedimentary records of the PETM and Eocene Thermal Maximum 2 (ETM2), a smaller magnitude hyperthermal that occurred ~ 2 My after the PETM (Fig. 1). During the Late Cretaceous–early Paleogene Laramide orogeny, the Bighorn Basin experienced rapid tectonic subsidence while adjacent mountain ranges were being uplifted. This combination of abundant accommodation space and high sediment flux from the erosion of the adjacent uplifts, led to the development of a very complete and expanded early Paleogene fluvial–lacustrine stratigraphic record for this time interval. Average sediment accumulation rates are on the order of 0.25–0.50 m kyr^{-1}, which translates into a ~ 50-meter-thick PETM interval. Fossils, especially vertebrates and plants, are abundant in the early Paleogene Bighorn Basin deposits and have been intensely studied for over a century (Gingerich, 1980; Bown et al., 1994; Wing et al., 1998; Gingerich and Clyde, 2001). Stratigraphic studies incorporating paleontological, sedimentological, and paleoclimatic data have been common for decades, with recent focus on hyperthermals (Koch et al., 1992; Clyde and Gingerich, 1998; Bowen et al., 2001; Wing et al., 2005; Gingerich, 2006; Secord et al., 2010; Abels et al., 2013). These studies, however, have been limited to sampling discontinuous exposures of weathered outcrops. By coring these sediments, we were able to collect continuous stratigraphic records of fresh, unweathered material of the PETM and ETM2 hyperthermals. By sampling these cores at high-resolution (1000–10 000 yr sampling interval), we can develop multi-proxy records for temperature, carbon cycling, and biotic change that will allow us to investigate, in an unprecedented way, the high-frequency climatic and biotic variability of a continental depositional system during greenhouse conditions.

2 Scientific goals and questions

Despite over a decade of intense research, many questions still remain concerning the causes and effects of hyperthermals. Although it is generally agreed that hyperthermals represent the geologically rapid injection of isotopically light carbon into the mixed ocean–atmosphere system, there is still no consensus as to the source(s) of this carbon and whether the PETM and other hyperthermals represent a continuum of the same process or represent fundamentally different processes (Sexton et al., 2011). We hope to use the continuous and expanded multi-proxy records of hyperthermals from the BBCP to better constrain the tempo and mode of associated changes in the carbon cycle, climate, ecosystem, and hydrology in this continental environment in an effort to better understand their causes and consequences. To focus the BBCP research, a series of guiding scientific questions were developed during the planning workshops leading up to the drilling. These include

- Can the internal carbon isotopic variability before, within, and after the PETM and ETM2 be used to correlate between terrestrial and marine records and does it reveal clues about the cause of these hyperthermals?
- Are there observable lags between the carbon isotope excursions (CIEs) and other paleoenvironmental indicators (e.g., temperature, precipitation, biomarkers, pollen)?
- Is ETM2 characterized by similar biotic changes as seen at the PETM?
- How are floral and faunal changes related during hyperthermals? Do faunas respond to floral change or vice versa?
- How did the PETM and other hyperthermals affect the hydrological cycle (e.g., monsoonal circulation) in the Rocky Mountain region?
- How did changes in the flora and changes in the hydrological cycle impact wildfire activity?
- What was the continental sedimentary response to the PETM and other hyperthermals (e.g., effects on pedogenesis)?
- Are the facies stacking patterns or geochemical records (e.g., XRF) in the Bighorn Basin cyclic?
- If these records show cyclicity, are the periods of those cycles consistent with predictions for astronomical control?
- If astronomically controlled, do the dominant periodicities change through the sequence and is there a relationship of this to the PETM or other hyperthermals?

3 Drilling summary

A BBCP Drilling Plan was developed during a series of meetings starting with a workshop in Powell, Wyoming, in June 2007 and culminating with a proposal to NSF in 2009 that was funded in October of 2010. After a final pre-drilling planning meeting at the Denver Museum of Nature and Science (DMNS) in March 2011, drilling began in July 2011 and was completed in August 2011. Drilling was carried out by Ruen Drilling, Inc. and down hole logging (magnetic susceptibility, resistivity, density, gamma, caliper) was done by Colog. Coring was carried out with a truck mounted HQ coring system (6.2 cm diameter) and cores were captured in a thin transparent Lexan liner. This protocol was used to mimic, as closely as possible, the IODP coring protocol because the BBCP cores were processed, logged for physical properties, XRF scanned, and archived in the Bremen Core Repository which also serves as one of the three IODP core repositories. Three sites were drilled, with two overlapping holes at each site.

3.1 Basin Substation

This site was chosen because outcrops in the area indicate that the PETM is preserved in a relatively organic-rich package of sediments here but the exposures are too poor for good surface sampling. Most PETM lithofacies in the Bighorn Basin are quite oxidized and thus very low in total organic matter so do not preserve abundant palynomorphs or biomarkers, both of which we hope to recover in the BBCP. By targeting the PETM sediment package at Basin Substation, we aim to maximize organic preservation so these methods can be successfully applied.

Coring at Basin Substation occurred between 13 and 17 July 2011 and two overlapping cores were drilled. One core (BBCP-BSN11-1A) was drilled to 138.4 m below surface (mbs) and the second core (BBCP-BSN11-1B) was drilled to 138.6 mbs (Table 1; Fig. 2). Both cores were drilled using only municipal water, thus minimizing potential organic contamination. Down hole geophysical logs were recovered to about 100 m depth.

3.2 Polecat Bench

Polecat Bench is the best documented continental record of the PETM known in the world. It is the site where (a) the oldest North American Artiodactyla, Perissodactyla, and true Primates defining the Paleocene–Eocene boundary were first found (Gingerich, 1989), (b) conspicuous dwarfing of mammals was first documented (Gingerich, 1989; Clyde and Gingerich, 1998), (c) the PETM carbon isotope anomaly was first found on land (Koch et al., 1992) and studied at high-resolution (Bowen et al., 2001) and (d) the CIE in organic carbon was first compared to that in paleosol carbonate (Magioncalda et al., 2004). Paleosols here have been studied

Table 1. Summary data for BBCP drilling sites.

Locality	Drill hole	Lat (N)	Lon (W)	Elev. (m)	Depth (m)	Core recovery (%)	Fluid	Target
Basin Substation	BBCP-BSN11-1A	44.4162583	108.1055664	1240.5	138.4	100.0	Municipal Water	PETM
Basin Substation	BBCP-BSN11-1B	44.4162042	108.1053154	1244.2	138.6	98.6	Municipal Water	PETM
Polecat Bench	BBCP-PCB11-2A	44.7688571	108.8879668	1588.1	130.0	99.0	Municipal Water	PETM
Polecat Bench	BBCP-PCB11-2B	44.7688782	108.8878902	1589.4	245.1	100.0	Bentonite + Polymer	PETM
Gilmore Hill	BBCP-GMH11-3A	44.5159525	108.6459393	1521.8	202.4	98.8	Municipal Water	Elmo/H2
Gilmore Hill	BBCP-GHM11-3B	44.5158935	108.6459018	1521.8	66.7	98.4	Municipal Water	Elmo/H2

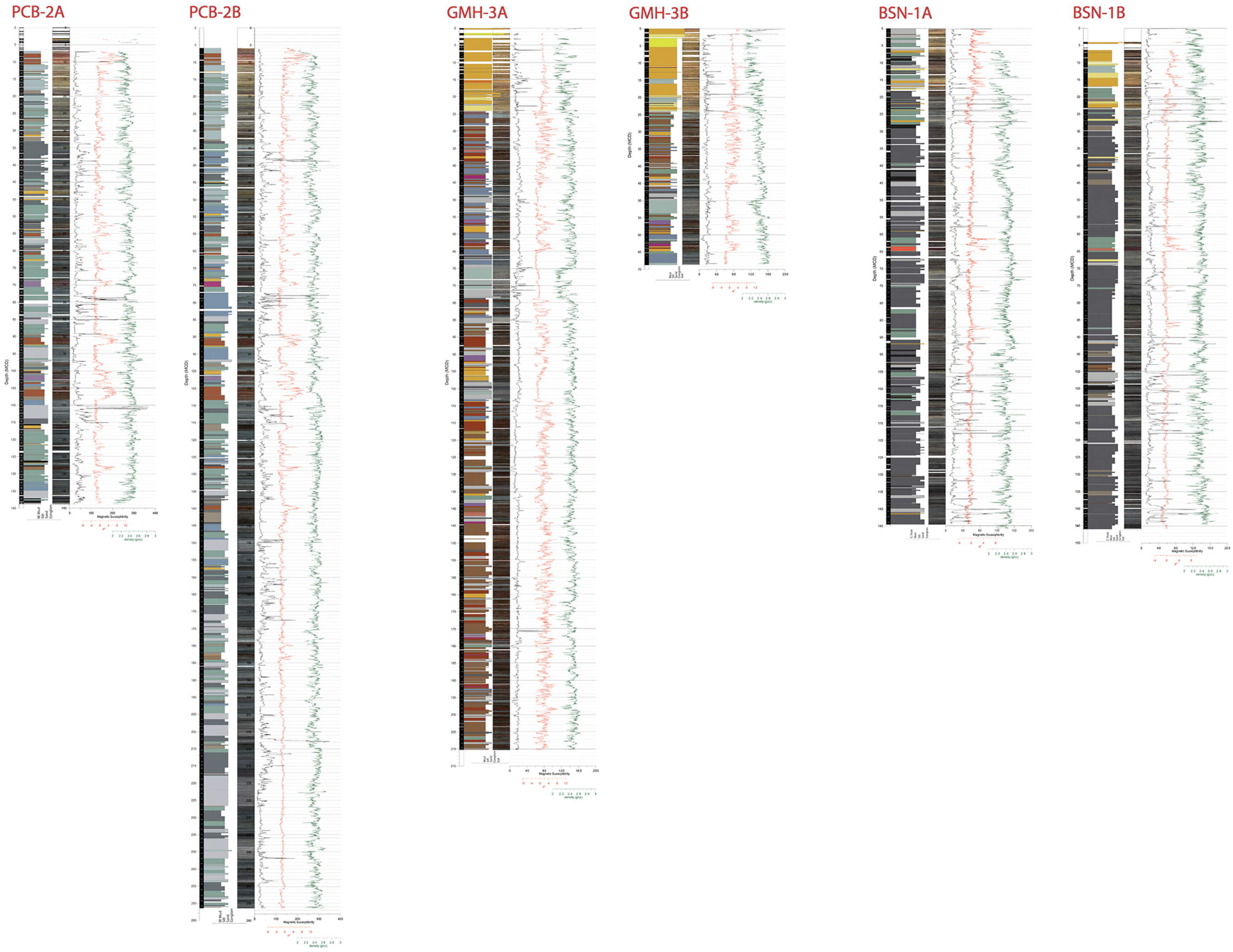

Figure 2. Lithological logs, line-scan images, magnetic susceptibility (black curves), color redness index a* (red curves), density (green curves) for each of the cores drilled during the BBCP. Cores are arrayed northwest (left) to southeast (right; see Fig. 1). PCB – Polecat Bench; GMH – Gilmore Hill; BSN – Basin Substation.

in detail from surrounding surface sections providing a 3-dimensional lithostratigraphy that can be correlated to the core records, thus linking these previous outcrop studies to the new core studies. Furthermore, the first attempt to recognize orbital cyclicity in a continental PETM section was done using a Polecat Bench surface section (Abdul-Aziz et al., 2008) so cores from here will provide an excellent mechanism to test, and expand on, that work.

From 18 to 25 July 2011 two overlapping cores were drilled at Polecat Bench. One core (BBCP-PCB11-2A) was drilled to 130.0 mbs and the second core (BBCP-PCB11-2B) to 245.1 mbs (Table 1; Fig. 2). The first core was drilled using only municipal water and the second was drilled with bentonite and polymer additives to stabilize the hole and maximize drilling depth and core recovery. Downhole geophysical logs were recovered for the entire 245 m of the second (B) hole.

3.3 Gilmore Hill

Outcrops in the Gilmore Hill area record one of the most complete sections that spans the Wa-4/Wa-5 biozone boundary (= "Biohorizon B") which is the largest mammalian turnover in the early Eocene after the PETM (Schankler, 1980; Chew, 2009). Recent isotopic sampling of surface sections in this area has also established the existence of an isotopic excursion that correlates to the ETM2/H2 interval (Abels et al., 2012). By retrieving core records from here, we hope to apply the various methods outlined above to better document the continental effects of non-PETM hyperthermals, further constrain their cause, and compare them to records of the PETM. Only by comparing detailed multiproxy records of multiple hyperthermals will it be possible to determine whether they share a common cause and whether they result in repeated, and thus predictable, environmental changes.

From 1 to 5 August 2011 two overlapping cores were drilled at Gilmore Hill. One core (BBCP-GMH11-3A) was drilled to 202.4 mbs and the second core (BBCP-GMH11-3B) was drilled to 66.7 mbs (Table 1; Fig. 2). Both cores were drilled using only municipal water and downhole geophysical logs were recovered for 89 m in the first hole and the entire 66 m of the second hole.

4 Core analysis and post-drilling science

After preliminary cataloging and describing of the BBCP cores in the field, they were shipped to the Bremen Core Repository (BCR) in a refrigerated container on 10 August 2011, where they arrived on 27 September 2011. We decided to utilize the BCR for a variety of reasons; two of the BBCP senior personnel (Röhl and Westerhold) are from the MARUM (University of Bremen), the BCR and adjacent MARUM laboratories have excellent core processing facilities and support staff, and it is the repository for several important PETM cores drilled in the Atlantic and Arctic Oceans (ODP and IODP). The BBCP science team converged at the BCR from 8 to 27 January 2012, to split, describe, scan, sample, and archive the cores. A BBCP Sample, Data and Obligations Policy[1] was developed and distributed before this meeting to ensure that the roles and responsibilities of scientists interested in working on the BBCP were clearly communicated ahead of time. The BBCP policy is strongly based on the equivalent IODP policy and includes a one-year data moratorium during which science team members have exclusive rights of access to BBCP material (core samples and data). After the one-year moratorium, non-BBCP science team investigators can make sample and data requests to the BBCP Sample Allocation Committee (SAC, consisting of WC, PG, SW, and UR).

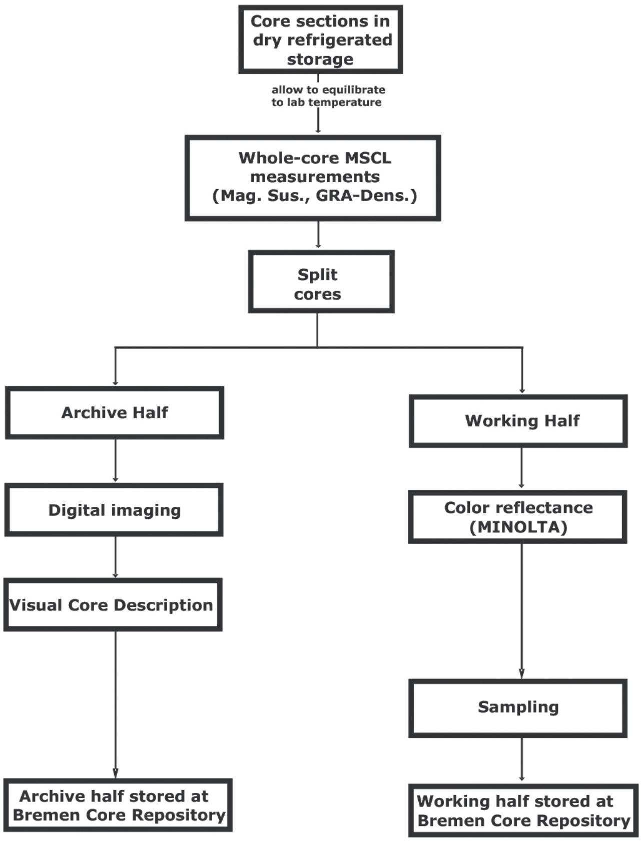

Figure 3. Work flow used to process BBCP cores at the Bremen Core Repository.

For the sampling and data acquisition meeting at the BCR, we modeled our core flow scheme after IODP and ICDP procedures (Fig. 3). Whole-core MSCL measurements (magnetic susceptibility [MS], gamma ray attenuation [GRA] – density) were performed at MARUM on a GEOTEK Multi-Sensor Core Logger (MSCL) before the science team arrived. During the meeting, cores were split with a water cooled diamond tipped core saw which worked well despite the existence of smectitic clays in the core materials. After splitting, the working halves were color scanned using a Minolta Spectrophotometer 2600d and then sampled before being archived in the refrigerated core storage facility at the BCR. Sampling was based on formal sample requests that were submitted by the science team before the meeting with stratigraphic resolution and sampling protocols varying depending on the sample type. Over 4500 samples were collected including samples for carbonate nodules, bulk organic carbon, paleomagnetism, vertebrate fossils, palynology, biomarkers, plant

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[1] http://earth.unh.edu/clyde/pdfs/BBCP_Sample_Policy.pdf

Table 2. Summary tally of samples from the BBCP initial sampling meeting.

	Drill hole						
Sample type	BSN 1A	BSN 1B	PCB 2A	PCB 2B	GMH 3A	GMH 3B	Total
Carbonate nodules	3	4	186	339	266	44	842
Bulk organic carbon	0	322	241	176	268	12	1019
Paleomagnetism	80	0	0	148	138	0	366
Vertebrate fossils	0	1	0	0	1	0	2
Palynology	0	296	214	170	238	0	918
Biomarkers	0	225	188	131	209	24	777
Plant cuticle	33	0	0	5	1	4	43
Sediment (grain size, XRF)	155	72	56	72	296	0	651
Total	271	920	885	1041	1417	84	4618

cuticle, and bulk sediment for grain size and XRF analysis (Table 2). The archive halves of the cores were line scanned using a 3 CCD digital image device attached to the Super-Slit XRF-core scanner. These line-scans produce visual color images and generate color data in RGB and CIE space that can be used to calculate commonly used color indices (e.g., L*, a*, b*). After line scanning, archive halves were visually described. Original handwritten description forms (Visual Core Descriptions-VCDs) were scanned to PDF, compiled for each hole, and archived. Basic lithological data were extracted from the VCDs and entered into a searchable lithological database before archiving the cores in the BCR. All data are stored in the ExpeditionDIS especially configured for this project, and for the science team members, in a login-protected data sharing web site (http://www.PBWorks.com).

In order to address the central BBCP science questions, the science team is applying a variety of different methodological approaches to the cores. XRF scanning of the archive halves of the cores is being carried out to evaluate patterns of variability in bulk geochemistry and determine whether these continental facies may record orbital cycles. To track changes in the carbon cycle and climate, and to correlate the cores to other terrestrial and marine records of hyperthermals, stable carbon and oxygen isotopes of paleosol nodules and bulk organic matter are being analyzed. Palynological analysis is the primary in situ tool for tracking ecological changes through time, although correlations to nearby outcrops with vertebrate and plant macro fossils are also important. Preliminary tests carried out on cuttings from a pilot drill hole near the Basin Substation site during 2007 indicated that subsurface samples had greater diversity and higher abundance of molecular biomarkers than samples collected from subaerially exposed outcrops so sampling was carried out on all of the cores in hopes of recovering biomarkers that can be informative about temperature change and ecological change (plant and microbial lipids, including alkanes, terpenoids, and hopanes). Patterns of change in wildfire activity have been proposed as a consequence of PETM climate change so BBCP cores were sampled for analysis of polycyclic aromatic hydrocarbons (PAHs) and for charcoal as proxies for wildfire activity. Paleomagnetic samples were collected to confirm the basic magnetic polarity stratigraphy observed from the overlapping outcrop record and to investigate potential geomagnetic and/or rock magnetic changes across the hyperthermals as have been reported elsewhere (Kopp et al., 2007; Lippert and Zachos, 2007; Schumann et al., 2008; Lee and Kodama, 2009). Certain parts of the cores with higher concentrations of organic carbon were sampled for plant cuticle in hopes of reconstructing $p\mathrm{CO}_2$. Grain size measurements and XRF analysis of bulk sediment samples were carried out to investigate patterns of lithological change across the hyperthermals and to help calibrate the XRF scanning data. Two vertebrate fossils were discovered in BBCP cores so these were collected for archiving at the University of Michigan Museum of Paleontology, where most of the vertebrate collections from nearby outcrops are located.

5 Initial results

One of the more important preliminary observations from the project is the relatively deep weathering horizons that were encountered. Although we knew that weathering depths were below the level that is practical to access by digging surface outcrops, we did not have a firm absolute estimate of them in this type of "badland" erosional environment. Assessment of the VCDs, line-scan images, and color data indicate that obvious weathering features (e.g., oxidation, hydration, fracturing) extend down ~ 20–30 m below the surface at all three drill sites (Fig. 4). The oxidation and hydration reactions most clearly impact the color of the cores, where the color index a* (redness/greenness) trends toward higher values (redder and yellower) in the weathered zone (Fig. 2). For instance, the bright red color of the paleosol bed at the top of the Polecat Bench cores (7–10 mcd, Fig. 4) is clearly accentuated by weathering compared to the muted red hues of the unweathered paleosols lower in the core (e.g., 57–59 mcd, Fig. 4). The Gilmore Hill cores seem to show the deepest weathering horizons, probably due to the ~ 20 m of poorly

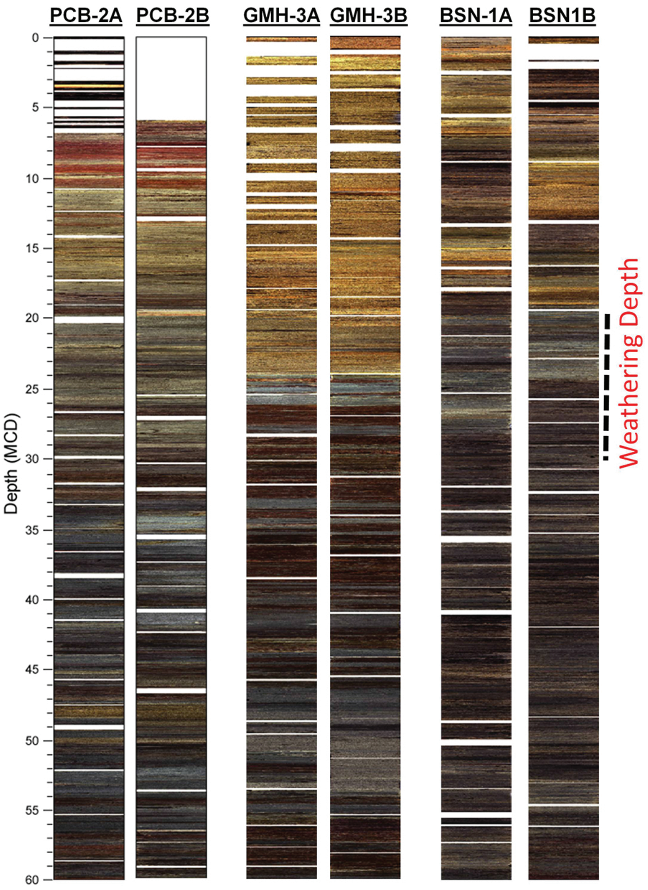

Figure 4. Line-scan images of the upper 60 m from each of the BBCP cores. Weathering depths of ~ 20–30 m are clear in the change from yellowish colors near the surface to drabber colors in the subsurface. Depth is scaled in meters composite depth (MCD).

cemented sandstone that lies at the tops of those cores, creating a highly permeable conduit for meteoric water to infiltrate downwards. The BBCP cores may provide an excellent natural laboratory to investigate the "critical zone" at the interface between the atmosphere and the lithosphere in this kind of erosional sedimentary environment.

Comparison of the lithological logs based on the VCDs with the logs of magnetic susceptibility, density, and color indicates several general patterns (Fig. 2). Below the weathered zone, color variations as expressed by the color index a* highlight the presence and frequency of reddish colored paleosols. These are important marker beds that can be used to correlate the cores to surface outcrops and thus provide key links to the previously published stratigraphic records from these areas. The Polecat Bench B core clearly shows the up-section increase in frequency of paleosol red beds that marks the Paleocene–Eocene boundary interval in the Bighorn Basin. The Basin Substation cores show relatively few red paleosols across the same interval, highlighting the less oxidized nature of this site which is why it was targeted for coring. The Gilmore Hill cores sample an interval about 2 million years younger than the PCB and BSN cores and are thus quite different from them in that they are dominated by paleosol red beds, with only minor occurrences of the less oxidized facies. Whereas the density logs are typical in tracking grain size, the magnetic susceptibility logs show several scales of variability, which we investigated in more detail in order to understand the processes driving this variability.

We carried out preliminary isothermal remanent magnetization (IRM) experiments on a series of discrete samples to better understand the underlying mineralogical factors that control magnetic susceptibility variability in these cores. Representative samples were collected from core depths showing low, medium, or high susceptibilities based on multi-sensor core logs. Bulk mass normalized susceptibility was measured for each sample and compared to the corresponding core log measurement. Only those samples that showed good agreement between measured susceptibility and core log data were analyzed further. A hard (1.1 T) IRM was acquired in a step-wise fashion along the z axis of each sample with subsequent back-field IRMs of −100 and −300 mT applied to further constrain the proportions of magnetic minerals with different coercivity. After reacquiring a 1.1 T IRM along the z axis, medium coercivity (0.4 mT) and low coercivity (0.12 mT) IRMs were acquired along the y and x axes, respectively, and the samples were thermally demagnetized in a step-wise fashion (Lowrie, 1990). Results show that the highest magnetic susceptibilities in the cores are associated with coarser deposits (sandstones and siltstones) that are enriched in detrital magnetite. Some mudstones have elevated magnetic susceptibility as well but in these cases it is caused by enrichment of hematite due to pedogenesis (Fig. 5).

Results from extensive previous research on outcrops in the areas surrounding the coring sites provides an excellent opportunity to compare proxy results recovered from stratigraphically overlapping cores and outcrops to explore the potential effects of weathering on these records. Sediment color in both the Fort Union and Willwood Formations are significantly different between core and outcrop and thus is clearly affected by weathering (see discussion above and Fig. 4). Although distinctly colored strata can be identified in, and correlated between, core and outcrop, the colors in the cores are muted compared to the highly accentuated weathered colors in the outcrops. Preliminary analysis of total organic carbon and stable carbon and oxygen isotopes in organic matter and carbonate indicate very little difference between core and outcrop results, although the oxygen isotopic composition of surface carbonate nodules may be slightly lower compared to core samples potentially due to interaction with meteoric water (Fig. 6a). Preservation of organic biomolecules, however, is clearly elevated in core samples relative to outcrop sample. For instance, terpenoids, hopanes and n-alkanes all exhibit significantly higher concentrations in sub-surface, unweathered samples compared to outcrop samples (e.g., Fig. 6b).

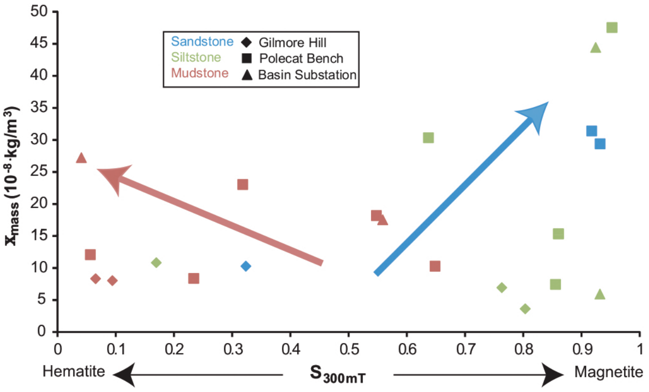

Figure 5. Magnetic susceptibility plotted against S ratio ($S_{300\,\text{mT}}$; Thompson and Oldfield, 1986) showing that the highest magnetic susceptibilities are associated with coarser deposits (sandstones and siltstones) enriched in detrital magnetite (higher S ratios) but that some mudstones have elevated magnetic susceptibility because of enriched hematite concentrations (lower S ratios) due to pedogenesis.

GDGTs (glycerol dialkyl glycerol tetraethers), compounds used as a paleotemperature proxy, were not detectable in either core or outcrop samples and were likely degraded by oxidative diagenesis and/or thermal maturation during burial. Pollen preservation is similar between core and outcrop samples of carbonaceous shales but core samples of oxidized paleosol units do produce rare sporomorphs, whereas outcrop samples of those facies tend to be barren.

6 Outreach

The Bighorn Basin preserves one of the most complete and fossiliferous stratigraphic sections of earth's sedimentary carapace. In collaboration with the Denver Museum of Nature and Science, we designed a multi-faceted outreach program to capitalize on this and make the basin into a natural classroom for educating the public about key scientific issues facing today's society – evolution, geological time, and climate change. To draw attention to the remarkable evolution of earth's environment and biota over long geological timescales, we are writing a small book that includes 12 landscape reconstruction paintings by illustrator Jan Vriesen (Fig. 7). This book is patterned after the successful *Ancient Denvers* book that capitalized on the well-studied stratigraphy and paleontology of the Denver Basin, sold more than 10 000 copies, and remains one of the region's most accessible portals to paleontology and geology. The book *Ancient Bighorn Basin* will include a brief overview of the basin's geology featuring a stratigraphic block diagram of the basin that illustrates the filling and exhumation of the basin and the creation of the modern landscape. Each prehistoric reconstruction will be paired with photographs of formations and fossils that document the evidence used to create the painting. Such a book should have tremendous appeal for the many tourists to the region (especially Yellowstone) and also provide, for the first time, accessible prehistory for the region's students and residents.

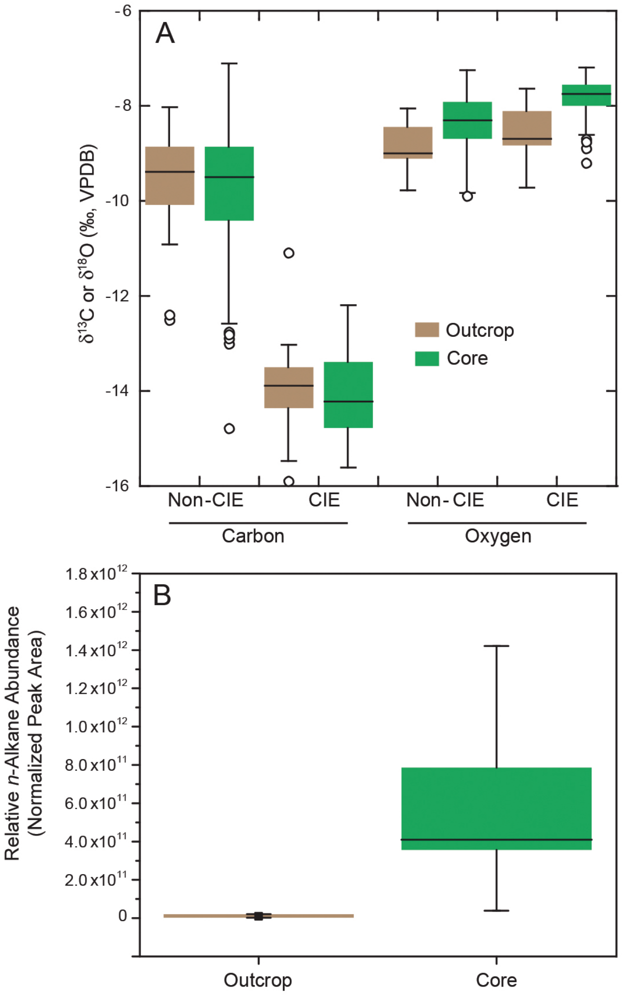

Figure 6. **(A)** Relative *n*-alkane abundances expressed as total FID peak area for C27, C29 and C31 *n*-alkanes corrected for injection ratio and mass of sediment extracted in non-PETM carbonaceous shale samples from Basin Substation core 1B (green, right) compared to adjacent outcrop samples (brown, left). *n*-Alkane peak areas in core samples are on average 60 times greater than in outcrop samples. **(B)** Stable carbon (left) and oxygen (right) isotope values of pedogenic carbonate samples from Polecat Bench cores 2A and 2B (green) compared to adjacent outcrop samples from the same beds. Samples are split between those stratigraphically within the PETM carbon isotope excursion (CIE) and those that fall outside that interval (non-CIE). Isotopic values from the cores overlap those from the outcrops quite closely with the possibility of a slight systematic offset in δ^{18}O values that could be associated with minor amounts of diagenetic alteration by local meteoric fluids in the outcrop samples.

Continental drilling is one of the few science activities that can be watched by the public and perceived as science

Figure 7. Eocene reconstruction scene painted by Jan Vriesen as part of BBCP outreach efforts. This is one of twelve Phanerozoic landscape reconstructions of the Bighorn Basin that Vriesen painted to increase awareness about earth-system variability over deep time and the unusually complete geological and paleontological record preserved in the basin. This scene shows an early Eocene floodplain forest with the large predatory flightless bird *Diatryma* (= *Gastornis*) in the background and the diminutive "dawn horse" horse *Hyracotherium* to the right.

in action. Another aspect of the BBCP outreach effort was to make live broadcasts from the Gilmore Hill drill site to schools and public audiences in the region. The *Science in Action* program at DMNS has pioneered the use of live two-way satellite broadcasts from field sites to classrooms. These two-way broadcasts allow live audience participation and conversations with the scientists on site. In order to have a multiplicative impact (and since the drilling was occurring during the summer when schools were out of session), we focused our program on groups of teachers so they could carry forward what they learned into their classrooms. The broadcasts were preceded by a lesson plan and informational video so participants were aware of the content and were primed to ask questions. In total we reached 173 teachers which should trickle down to well over 10 000 students.

One often overlooked audience for outreach is the group of scientists who may undertake similar scientific activities in the future and may benefit from the experiences of the current project. There has been considerable recent focus on growing continental scientific drilling activity in the US to help investigate, and provide new perspectives on, some of the major ongoing questions of earth sciences (Brigham-Grette et al., 2011; Walton et al., 2009, 2010). One of the limiting factors in implementing this plan, however, has been the relatively limited number of earth scientists with relevant training and experience in continental scientific drilling as well as the lack of drilling as a common tool in the deep-time scientific culture. In order to help educate scientists who have no experience with scientific drilling but may benefit from core records in their research, we have produced a 25 min video about continental drilling for the scientific community. This video documents the key steps in developing and implementing a continental scientific drilling project (e.g., planning, proposal development, drilling operations, post-drilling science). The video aims to help overcome that lack of experience and familiarity by educating the community about the benefits of continental core records and describing the logistical steps that must be taken to recover them. DVDs are being provided to relevant organizations for distribution at scientific meetings and the video file has been posted on YouTube and the project website.

Aside from these formal elements of the outreach plan, we also carried out many informal activities including on-site tours with a simple informational brochure for local residents and students (e.g., geology field camps passing through), an active Facebook page that helped non-resident team members and other interested parties to keep up on drilling progress, a science blog on the Smithsonian National Museum of Natural History web page, a presentation at the local natural history museum in Worland, Wyoming, and many interviews with the press that resulted in local, national and international news items. During the Science Party in Bremen the local daily newspaper (circulation 170 000 copies) became interested in the project and published an article in their science section.

7 Future scientific research

The BBCP is currently in the post-drilling science phase of the project. Preliminary BBCP results were presented at a 2012 AGU special session entitled “Continental Records of Early Paleogene Hyperthermals” and at EGU 2013 in the “Major Achievements and Perspectives in Scientific Ocean and Continental Drilling” session. We expect peer-reviewed publications detailing BBCP results to start appearing in the next year. Given the high core recovery rates and relative ease of drilling these kinds of continental fluvial sediments, we expect the BBCP will catalyze more scientific drilling activity in the relatively expanded stratigraphic records of intermontane basinal settings like the Bighorn Basin.

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Scientific Drilling
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Scientific drilling and downhole fluid sampling of a natural CO_2 reservoir, Green River, Utah

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1 Introduction

Understanding the geochemical behaviour of gaseous and supercritical carbon dioxide stored in geological reservoirs, over a range of timescales, is crucial for quantifying leakage risk and the geochemical evolution of the stored CO_2 through the life of an individual storage site (e.g. Bickle, 2009). Dissolution of the stored CO_2 into reservoir brine will likely form an important mechanism for stabilizing the CO_2 in geological reservoirs (e.g. Gilfillan et al., 2009; see review in Kampman et al., 2013a). Reactions between the acidified CO_2-charged brine and reservoir minerals might enhance the long-term storage of CO_2 by precipitation of carbonate minerals, or facilitate leakage by corroding cap rocks and fault seals. Understanding the fluid–fluid and fluid–rock reactions that may retard the migration of CO_2 from deep storage sites to the surface is also of critical importance for demonstrating the retentive capacity of the geological overburden above deep storage reservoirs.

Modelling the progress of the fluid–rock reactions is limited by uncertainties in the absolute mineral surface reaction rates and the unknown significance of other rate limiting steps such as CO_2 dissolution, and rates of fluid and solute transport (Knauss et al., 2005; White and Brantley, 2003). Investigating natural accumulations of CO_2 can provide insight into the consequences for geological materials from long-term exposure of supercritical CO_2 and acidic CO_2-charged brine. Whilst it is expected that a well-sited CO_2 storage facility will not leak, some natural CO_2 reservoirs (such as the Green River site) have conductive features where CO_2 and CO_2-charged fluids are able to escape from depth to surface. These can provide sampling opportunities and insights into processes that may inhibit CO_2 migration through the overburden, such as dissolution into shallow reservoirs, capillary trapping of CO_2 gas or precipitation of carbonate minerals.

Deep geological storage of anthropogenic CO_2 will involve injection at depths >800 m up to several kilometres, where the CO_2 is in a supercritical state and formation temperatures can range from ~ 30 to >80 °C. The geochemical reactions occurring in CO_2 reservoirs, including dissolution into brine, and the subsequent reaction of the CO_2-charged brine with reservoir minerals are all sensitive to temperature. However, thermodynamic parameters such as the degree of CO_2 and mineral saturation in the fluid, or physical parameters related to flow of the CO_2, or surface properties of the minerals are equally as important in controlling the rates of these geochemical processes. Observations from shallow reservoirs containing CO_2-charged brine are thus extremely informative on the fundamental physical and geochemical processes controlling these reactions, and processes that may inhibit CO_2 migration to the surface. The current state of knowledge of fluid flow and geochemical processes occurring during the storage of CO_2 in sedimentary basins is reviewed in Kampman et al. (2013a) and Jun et al. (2012). Natural analogue sites are reviewed in Baines and Worden (2004) and fluid–rock reactions in natural accumulations of CO_2 are reviewed in Bickle et al. (2013). The behaviour of cap rocks is reviewed in Song and Zhang (2012) and geochemical processes occurring during CO_2 leakage are reviewed in Harvey et al. (2012).

2 Project objectives

The fundamental goals of this project are to characterise and understand the mineralogical, geochemical, petrophysical and geomechanical consequences of long-term exposure of supercritical CO_2, CO_2-gas and CO_2-charged fluids on reservoir rocks, cap rocks and fault zone materials. This will improve our predictions of the long-term security of anthropogenic CO_2 geological storage sites. Data gathered during the extensive laboratory study of samples collected during drilling will be used to define or verify coupled models, like reactive transport (flow and geochemical reactions) or geochemical-mechanical models; these are ongoing projects at Shell Global Solutions International and the University of Cambridge. Despite the wide occurrence of natural CO_2 reservoirs, by their nature the critical parts of the reservoirs are buried and can only be accessed by drilling. If cap rocks, reservoir rocks or fault systems within reservoirs are exposed, not only will the CO_2-bearing fluids have already escaped, but the mineralogy and chemistry of the reservoir rocks will be altered by diagenetic and weathering reactions; thus the critical aspects of a breached system can only be inferred by indirect means. For these reasons the scientific drilling project had two primary objectives: (i) the recovery and preservation of core-samples from reservoir and caprocks exposed to CO_2 and CO_2-rich fluids; and (ii) the recovery of uncontaminated fluids at formation pressures from the target reservoirs using a wireline fluid sampler, and the analysis and collection of their dissolved gas load and fluid pH at surface. In this contribution we focus on the drilling operation itself and the sample recovery, and provide a brief description of the fluid sampling results. Details of the study of the core-samples and fluid geochemistry are ongoing; the initial results are presented in Kampman et al. (2013b), and detailed analyses of the reservoir and cap rock core-samples will be presented in future publications.

3 Green River CO_2 System

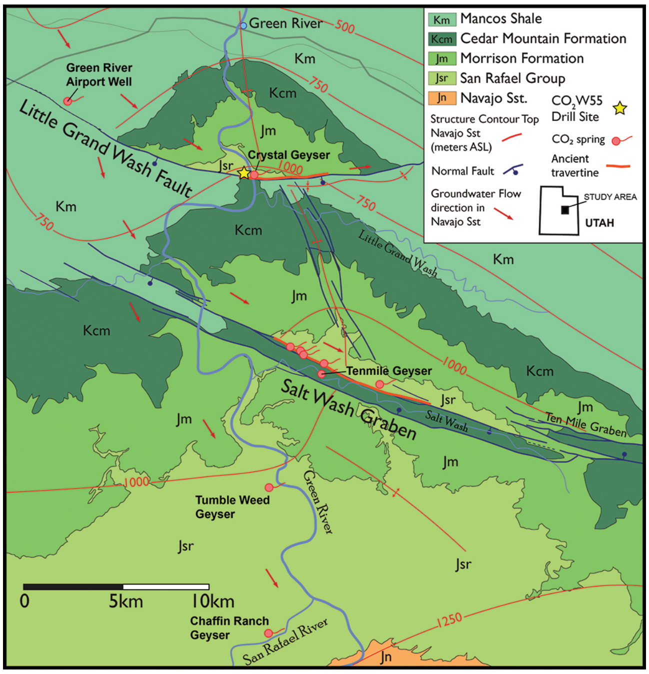

Figure 1. Geological map of the Green River anticline showing locations of the Little Grand Wash and Salt Wash Graben normal fault systems, CO_2-springs and location of drill hole CO2W55 (base map redrawn after Doelling, 2001 and Kampman et al., 2009). The distribution of ancient travertine mounds along the faults is highlighted, reflecting sites of paleo-CO_2 leakage (drawn from maps in Dockrill and Shipton, 2010). Structure contours are the height of the top surface of the Navajo Sandstone above sea level, the main shallow CO_2 bearing reservoir. Groundwater flow trajectories in the Navajo Sandstone are also shown (after Hood and Patterson, 1984 and maps in Kampman et al., 2009). Meteoric fluid flows from recharge zones in the San Rafael Swell to the northwest to zones of discharge in the Green River. The CO_2 and CO_2-charged brine flowing up the faults, mix with meteoric fluids in the Navajo Sandstone and flow parallel to the faults where they are sealing, and to the south-east where they are transmissive, being driven by the regional gradient in groundwater head.

Numerous natural accumulations of supercritical CO_2 and CO_2-dominant gases occur throughout the greater Colorado Plateau and Southern Rocky Mountains region (Allis et al., 2001; reviewed in Bickle et al., 2013). A small number of these accumulations possess fault-associated, surface travertine deposits attesting to CO_2 leakage in the recent and geological past; the Springerville-St Johns Field, Arizona; Farnham Dome, Utah; and Green River, Utah. Of these only the Green River accumulation, and the St Johns Dome site (Allis et al., 2005, Gilfillan et al., 2011) are known to be naturally leaking in the present day.

Oil exploration drilling along the Green River anticline (Fig. 1) has encountered accumulations of CO_2-charged brine in the Navajo Sandstone at depths of ~200–340 m; CO_2 gas and CO_2-charged brine in the Jurassic Wingate sandstones at depths of ~400–500 m; accumulations of supercritical CO_2 and CO_2-charged brine in the Permian White Rim Sandstone at depths of ~800–900 m; and supercritical CO_2 and CO_2-charged brine in Carboniferous

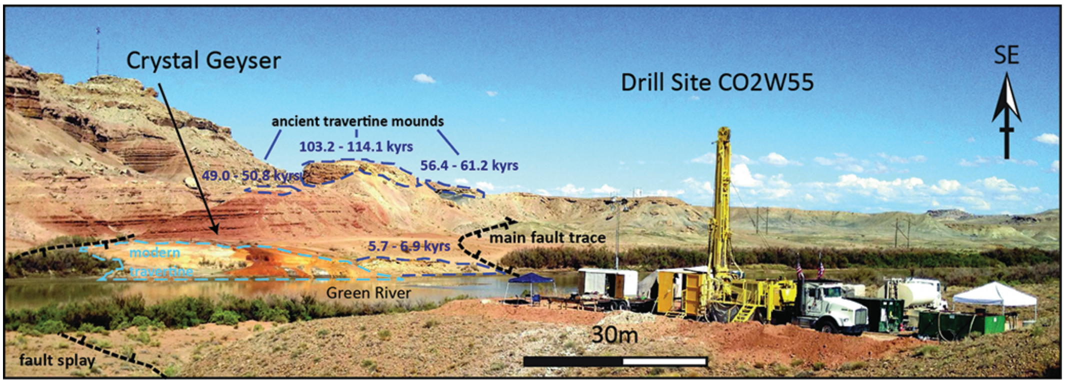

Figure 2. Field photograph of the drill site of well CO2W55 showing the CS4002 Truck Mounted Core Drill in the foreground and the travertine mound formed by Crystal Geyser on the opposite bank of the Green River. Also shown are the main fault trace of the Little Grand Wash Fault, and the local fault splays. Ancient travertine mounds form away from the main fault trace, within the footwall block of the fault, above the main fault damage zone through which CO_2 and CO_2-charged brine escape to surface. Travertine mound ages from Burnside et al. (2013) are also shown.

(Pennsylvanian and Mississippian) aged carbonate and evaporite deposits at depths > 900 m (J. Beach, Delta Petroleum, personal communication, 2007, e.g. Navajo Sandstone – Greentown State 36-11, API 4301931462; Wingate – Greentown Federal 26-43D, API 4301931547; White Rim – Green Town Federal 35-12, API 4301931507). CO_2 and CO_2-laden water leaks to the surface along the crest of the Green River anticline through a number of abandoned petroleum exploration wells and through the damage zone of the footwall block of the Little Grand Wash and Salt Wash normal fault systems (Figs. 1–3; Dockrill and Shipton, 2010; Shipton et al., 2004, 2005). These large normal faults (~ 35 km lateral extent) contain a clay gouge core. From surface mapping and projection onto Allen diagrams it is likely that they are laterally sealing towards the centre of the faults, with throws of 250–300 m, becoming laterally transmissive towards the fault tips, where reservoir–reservoir rock is juxtaposed (Dockrill and Shipton, 2010). Buoyant supercritical and gaseous CO_2 is thought to accumulate at the anticlinal crest adjacent to the two faults, beneath the south dipping fault seals. The localization of CO_2 leakage to the crest of the anticline reflects this, where open fractures in the fault damage zone allow CO_2 and CO_2-charged water to escape upwards from the deep supercritical CO_2 reservoirs (e.g. Pasala et al., 2013). In addition, an oil seep within the Little Grand Wash fault damage zone, near its intersection with the anticline crest, has been compositionally fingerprinted to Pennsylvanian strata at local depths of > 2 km, demonstrating migration of fluid from significant depths within the basin (Shipton et al., 2004). CO_2-leakage points away from the faults (Fig. 1; Tumble Weed Geyser and Chaffin Ranch Geyser) occur where exploration or water-well drill holes penetrate fluids in the Navajo Sandstone flowing horizontally away from the fault tips (Kampman et al., 2009).

U-Th dating of travertine mounds at surface shows a protracted history of CO_2 leakage over the past ~ 400 000 yr (Burnside et al., 2013), characterized by successive pulses of CO_2 degassing (Kampman et al., 2012). Over the last 135 000 yr pulsed leakage from the faults has occurred at the transition from local glacial to interglacial conditions. This has been likely triggered by changes in the hydraulic conductivity of the fault damage zone driven by changes in hydrology, pore fluid pressures and regional stresses following local climactic warming and crustal unloading (Kampman et al., 2012).

The stacked sequence of reservoirs, the relatively shallow depth (160–350 m) of the upper CO_2-bearing reservoir, the Navajo Sandstone and the prior knowledge of the site made it an excellent drilling target (Assayag et al., 2009; Baer and Rigby, 1978; Burnside et al., 2013; Dockrill and Shipton, 2010; Evans et al., 2004; Gouveia and Friedmann, 2006; Gouveia et al., 2005; Han et al., 2013; Heath, 2004; Kampman et al., 2009, 2012; Shipton et al., 2004, 2005; Wigley et al., 2012, 2013a, b; Wilkinson et al., 2009).

4 Drilling operations

Drilling of CO2W55 was carried out from 2 to 28 July 2012 using a CS4002 Truck Mounted Core Drill (Figs. 2–3). The drill site was located on the footwall block of Little Grand Wash Fault (38.93792° N, 110.13892° W; 1238 m Elev.), ~ 250 m to the west of Crystal Geyser – an abandoned petroleum exploration well, that now hosts a CO_2-driven cold water geyser (Fig. 3; Assayag et al., 2009; Baer and Rigby, 1978; Gouveia and Friedmann, 2006; Gouveia et al., 2005; Han et al., 2013). The initial drilling plan was to recover core by diamond drilling through a series of cap rock-reservoir pairs, from the Entrada Sandstone through to the base of the Permian White Rim Sandstone, at a proposed depth of ~ 815 metres below surface (m b.s.). The target CO_2-reservoir intervals included Jurassic and Permian sandstones of the Navajo, Wingate and White Rim formations, and cap rocks of the Carmel, Kayenta, Chinle and Moenkopi Formations. For technical reasons related to high volumes of fluid returns to surface, driven by degassing of the CO_2-charged brine within the well bore and expansion of the exsolved CO_2 gas during coring, drilling ceased at 322.5 m b.s. near the base of the Navajo Sandstone.

The hole was drilled vertically using DOSECC's hybrid coring system to recover core to a depth of 282 m b.s., with core recovery > 99 %, after which point the drill hole was completed by rotary drilling to a total depth of 322.5 m b.s. On-site processing of the core involved rinsing the core with water to remove drilling mud, core description, photographing and selective anaerobic bagging of important core sections in nitrogen-flushed vacuum-packed aluminised bags. Six samples of cap rock were also placed in preservation cells under axial-compression (G-clamped), to reduce mechanic degradation of the core, and for later testing in the laboratory of their transport properties (porosity, permeability, capillary entry pressure). Initial core descriptions were conducted based on macroscopic and microscopic investigations of the material. Fluid returns to surface from transmissive formations were sampled at the well head during drilling, filtered on-site through 0.2 μm nylon filters and stored in pre-cleaned high-density polyethylene bottles, prewashed with filtrate, one sample acidified to pH ~ 2–3 with 6M HCl and one un-acidified sample, for chemical analyses. Additional downhole fluid sampling was conducted in the Navajo Sandstone and is discussed in detail below. Downhole logging of the hole was not conducted due to the depth of cementation required to control fluid inflow into the drill hole (see below), with the cement layer impeding analysis using traditional formation logging tools.

The drill hole was spudded on 6 July; we initially drilled from 0 to 10.2 m b.s. with a 5-5/8 inch nominal (142.88 mm) diameter tricone rock bit, through the regolith to the "earthy" member of the Entrada Formation, and installed a temporary top casing of PVC pipe. Diamond coring with HQ core bits proceeded from 10.2 m down to 163.4 m b.s., through the "earthy" and "sandy" members of the Entrada Formation, at a penetration rate of ~ 70 m d^{-1}, to a point roughly ~ 14.0 m into the more competent underlying Carmel Formation (149 m b.s.). A bentonite based drilling mud was used with Max Gel and M-I Wate polymers, and a Soda Ash pH modifier was added during drilling within the Navajo Sandstone. The hole was re-drilled from 10.2 to 163 m b.s. with an 8-3/4 inch (222.25 mm) tricone rock bit, and permanent 6-5/8 inch (168.28 mm) diameter steel casing was cemented in place. Significantly, free CO_2 gas and CO_2-charged fluids were first encountered in the basal 35–150 m of the Entrada Sandstone, which is open to the surface in this region, indicating that thin siltstone layers (such as those within the Entrada) can act as effective seals to the upward migration of CO_2 and CO_2-charged fluids. Zones of CO_2-bearing fluids were identified based on the presence of CO_2-degassing and bubbling observed in intervals of core during washing, and CO_2-charged fluid returns to surface. The CO_2 gas pockets were identified during tripping out of the rods from the drill hole, where the gas / fluid ratio in fluid returns to surface would rapidly increase when the base of the rods encountered a zone in the formation containing CO_2 gas.

The Entrada Formation overlies the Carmel Formation, which in turn acts as the regional cap rock for the Navajo sandstone. As expected, the Carmel Formation produced no water while drilling with the exception of a conducting fault damage zone at ~ 188 m b.s. Drilling was smooth through the Carmel Formation, at a penetration rate of ~ 20 m d^{-1}, into the Navajo Sandstone, where the penetration rates increased to around ~ 50 m d^{-1}. Within the Navajo Sandstone, the reservoir overpressure and gas lift generated from degassing of the CO_2-charged brine within the wellbore began to return water to the surface. Shut in pressures were recorded periodically during drilling. Zero shut in pressure was observed during drilling through the Entrada Sandstone, Carmel Formation and through much of the upper Navajo Sandstone, suggesting pressure communication between the formations transected by the drill hole and Crystal Geyser (which as a flowing well acts as a pressure release). Within the Navajo Sandstone a maximum shut-in pressure of 13.8 bar was measured at surface at a drill hole depth of 221 m b.s., equivalent to a downhole pressure of 35.5 bar and formation overpressure of 12.8 bar. No continuous free gas flow (other than that degassed from the fluid within the well-bore) was observed at the well head whilst drilling in the Navajo Sandstone, even when the hole was unweighted with drilling mud, suggesting that the drill hole did not penetrate a free CO_2-gas cap within the Navajo Sandstone, or at least not a substantial one.

At around ~ 200 m b.s. the drilling mud used to weight the hole began to escape into the formation and became diluted by rapid inflow of formation fluid, resulting in partial unweighting of the hole, and an increase in water returns to surface. In order to alleviate the problem of heavy water returns and excessive gas lift at ~ 245 m b.s., the hole was cemented to seal this interval, and re-drilled. At 227.4 m b.s. we switched from HQ to NQ coring, and continued through the Navajo Sandstone to 282.2 m b.s. Following continued trouble with pressure control, gas lift and heavy water returns at 282 m b.s., the hole was again conditioned and then cemented. As the Navajo Sandstone is a relatively homogeneous unit it was decided to continue drilling with an 3-7/8 inch (98.43 mm) tricone bit until 322.5 m, an estimated 3 m into the Kayenta Formation, to take a final water sample at the base of the Navajo before the hole was plugged with cement and abandoned.

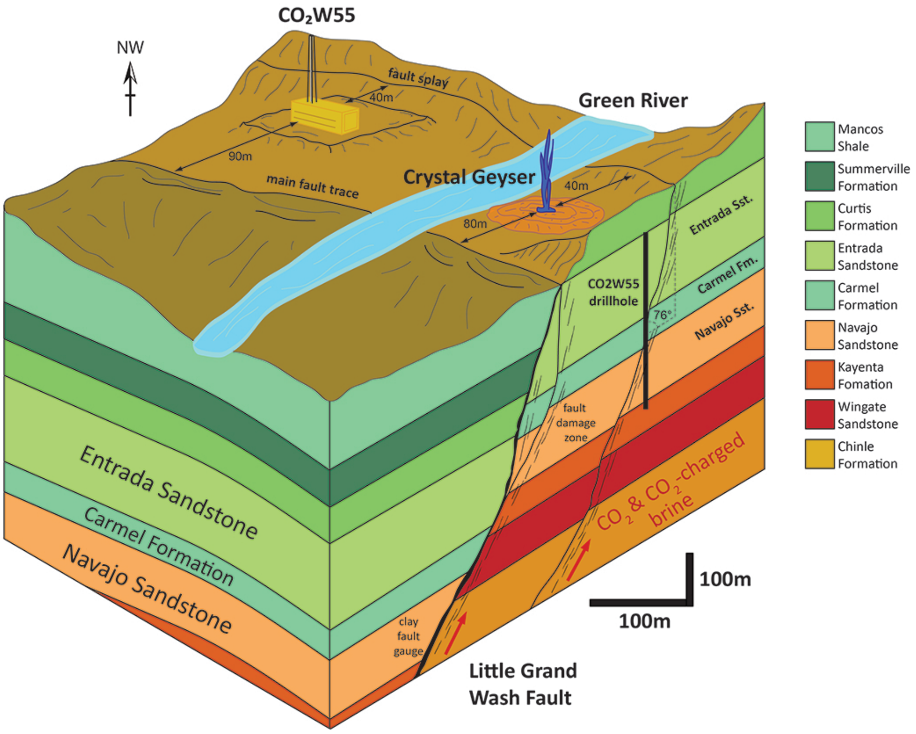

Figure 3. Cross section of the region surrounding drill hole CO2W55 showing the location of the Little Grand Wash fault system, including the northerly fault transacted by the drill hole (limited exposure precluded mapping this at surface), and the CO_2-driven cold water geyser at Crystal Geyser. The transect taken by the drill hole is projected on the left-side of the figure. The general structure of the fault is also shown using information from field mapping and in Shipton et al. (2004) and Dockrill and Shipton (2010).

5 Downhole fluid sampling at low pressure

Collecting uncontaminated and undegassed CO_2-rich fluid samples was a key objective of the Green River Drilling project. These CO_2-rich fluids contain a significant dissolved gas load, which will degas if exposed to pressures lower than the formation pressures. To prevent this, fluids were collected downhole at formation pressure by using the Leutert Bottom Hole Positive Displacement Sampler (Fig. 4a; PDS sampler) during the course of drilling (see also Kietäväinen et al., 2013 and Regenspurg et al., 2010 for examples of use of the tool in completed wells). Four fluid samples (~ 0.6 L) were collected from within the Navajo Sandstone formation at depths of 206 m b.s., 224 m b.s., 276 m b.s. and 322 m b.s. The use of the PDS sampler to recover pressurized fluid samples, fluid subsampling and the extraction of the fluid dissolved gas load for later compositional analysis in the laboratory is described in Regenspurg et al. (2010). Additional methods to analyse the dissolved CO_2 load of the fluid and fluid pH at high pressure in the field are discussed below.

We wanted the collected fluid samples to be (i) as little contaminated with drilling mud as possible and (ii) not depressurized and allowed to degas CO_2. The following protocol was initiated following a process of trial and error. Fluid sampling was conducted during the course of drilling the hole to avoid the need to pack in individual target sample depths. Drilling commenced to a predetermined sample depth at which point a fluid sample was taken. The PDS sampler is designed with a clock that opens the sampler after a set time and fills at a slow rate controlled by the down-hole pressure, an internal flow regulator and the pressure of an internal transfer fluid. The clock was set to allow enough time for the sampler to reach the base of the hole on wireline, for the natural overpressure to flush out the drilling mud, and for the formation pressure to recover. To do this a blow out preventer (BOP) was fitted with a lubricator assembly, the PDS sampler was lowered to the base of the hole, and the rods were then pulled up ~ 1.5 m, allowing formation water to flow for about 15–45 min, flushing drilling mud out of the hole using the natural overpressure of the formation. Following the flushing procedure, the well was shut in at the BOP, allowing pressure recovery for 1–2 h. The PDS sampler was then left down the hole for 5–6 h after the clock triggered to open the sampler. The long filling time was necessary because of the low reservoir pressures of ~ 35 bars, and the primary design of the tool for use at high formation pressures. Different combinations of flow regulator and internal transfer fluid pressure were attempted, but the filling time could not be reduced. Complete filling of the sampler with formation fluid triggers the sampler to close, trapping the fluid at the

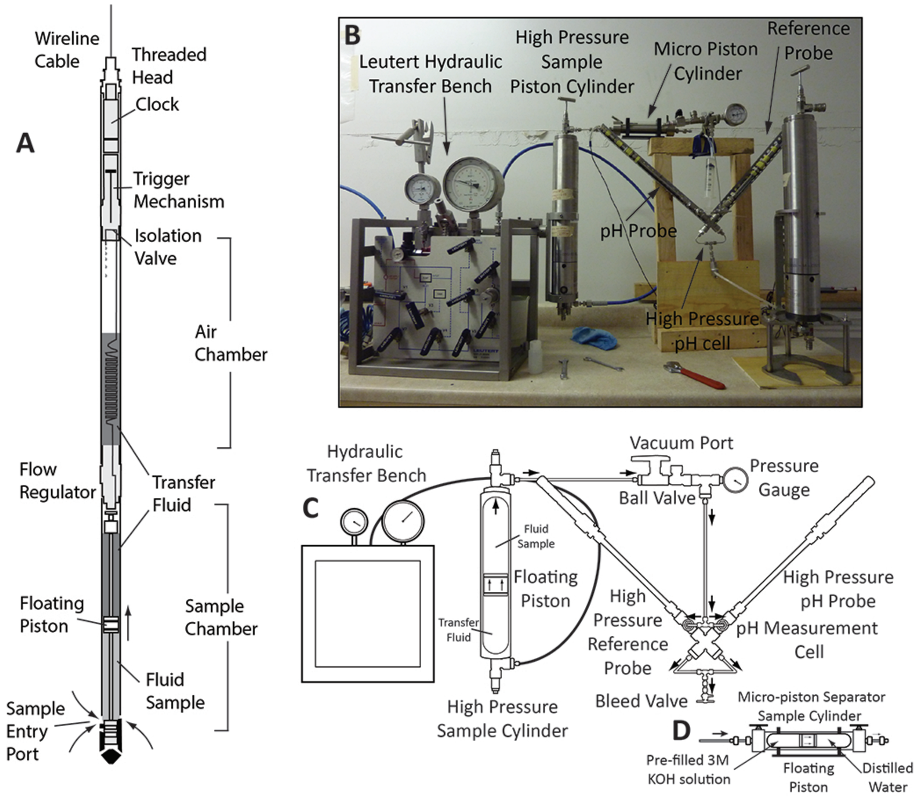

Figure 4. **(A)** Leutert Bottom Hole Positive Displacement Sampler (PDS sampler). **(B)** Laboratory set-up for extraction of high pressure fluid samples from the downhole fluid sampler for analysis of fluid CO_2 content and pH, in the field. **(C)** Showns the set-up for analysis of pH on pressurized samples. **(D)** The micro-piston cylinder used for the "alkalinity capture" of the dissolved CO_2.

formation pressure, after which the sampler can be recovered to surface on wireline.

The recovered fluid samples in the downhole sampler were transferred at pressure into high pressure piston separator sample cylinders, using a hydraulic transfer pump, to ensure the fluid did not degas (Fig. 4). A ~ 20–30 mL aliquot of the fluid was pumped from the piston sample cylinder through a high-pressure pH probe assembly, initially filled with a reference solution at the estimated formation pressure, and containing high pressure pH and reference probe (Corr Instruments). The pH cell was flushed with formation fluid until a stable pH was attained. A second aliquot of sample was pumped at pressure into a 30 mL micro piston separator. This was filled with 15 mL of 3M KOH solution, to capture the dissolved CO_2 in solution by conversion to CO_3^{2-} and precipitation as K_2CO_3, from which total CO_2 concentration could be determined by Gran titration. A sample of the exsolved CO_2 gas, for analysis of carbon and noble gas isotopic compositions, was then collected from the piston sample cylinder by connecting a length of refrigeration grade copper tubing to the pressure cylinder with high pressure lines, fittings and valves. These were in turn connected to pressure gauges and a roughing pump, to allow complete evacuation of atmosphere from the line and copper tubing before filling. The piston sample cylinder was allowed to depressurise rapidly, by the removal of back pressure across the separator piston, and the exsolved gas was collected into the copper tubing which was then sealed by cold welding with an aluminium sample bracket equipped with steel compression jaws. It is hoped that the vigorous degassing and much higher solubility of the noble gases in the CO_2 phase will enable quantitative noble gas recovery from the fluid, although the analyses are still pending and partial recovery should not impact the isotope ratios of the noble gases. The remaining fluid was then pumped through 0.2 µm nylon filters and stored in pre-cleaned high-density polyethylene bottles, prewashed with filtrate, one sample acidified to pH ~ 2–3 with 6M HCl and one un-acidified sample for chemical analyses.

6 CO2W55 core stratigraphy

The drill hole from the surface to 25 m b.s. encountered marine and lacustrine red siltstones facies of the "earthy" Entrada Sandstone member, that grade into the 125 m-thick bleached aeolian dune deposits of the lower Entrada Sandstone, with intercalated marginal marine and sabkha influences throughout (see Crabaugh and Kocurek, 1993). Sandstone units of the upper Entrada contain sporadic hydrocarbon and bitumen bearing zones, typically beneath siltstone seals from 35 to 50 m b.s. A series of sharp sub-horizontal contacts separate unbleached red siltstone and sandstone units from the bleached basal sandstone units. Steep bleached-unbleached contacts are observed around high-angle open fractures in the unbleached upper sandstone and siltstone units of the Entrada Sandstone. A complete sedimentary log of the cored interval is shown in Fig. 5 and examples of important intervals of the core are shown in Fig. 6. The total recovered thickness of Entrada Sandstone (~ 149 m) exceeds thickness estimates to the west and south (125 m) (O'Sullivan, 1981), indicating local thickening of the interval.

Below the Entrada Sandstone lies the Carmel Formation (top at 149 m b.s.), a 50 m-thick complex package consisting of three laterally gradational lithofacies: (i) interbedded, unfossiliferous red and grey shale and bedded gypsum; (ii) red and grey claystone/siltstone; and (iii) fine-grained sandstone. These are interpreted as marine sediments deposited in quiet, subtidal conditions under the influence of periodic hypersaline water (see Blakey et al., 1996 and references therein). Faulting at depths between 156 to 173 m b.s. has resulted in the formation of a ~ 17 m thick fracture zone comprising a ~ 7 m thick core containing centimetre to metre scale blocks of siltstone and shale breccia hosted in beds of remobilized gypsum. The core is bound by a fracture zone of gypsum-filled open fractures, of ~ 2 m thickness in the hangwall and ~ 8 m thickness in the footwall. Slickenlines and millimetre to centimetre displacements where observed on some fracture surfaces. The fracture zone in the footwall block was found to be transmissive, and surface returns of fluid were sampled. The recovered thickness of the Carmel Formation is consistent with regional estimates of 45–65 m, suggesting little loss of section. The limestone beds typical of the lower 1/3 of the Carmel Formation elsewhere (O'Sullivan, 1981) are locally thinned to ~ 2 m thickness, compared to a thickness of 10–15 m in the San Rafael Swell, 35 km to the west. The Carmel Formation forms a regional seal for the underlying Jurassic Navajo Sandstone (Peterson and Turner-Peterson, 1989).

In the CO2W55 core the Navajo Sandstone is comprised of thick sets of high-angle, cross-bedded, well-sorted, fine- to medium-grained sandstones with intercalated inter-dune facies sandstones which are typical of this aeolian deposit (see Verlander, 1995 and references therein). A thin zone of hydrocarbon bearing sandstone is present from 202 to 204 m b.s., beneath the Carmel Formation cap rock. Within the entire cored interval the unit is bleached from its typical red colour, to pale pink and white due to dissolution of hematite coatings originally present on the sand grains. Bleaching is most intense around open fractures and these are frequently mineralized with assemblages of gypsum and pyrite.

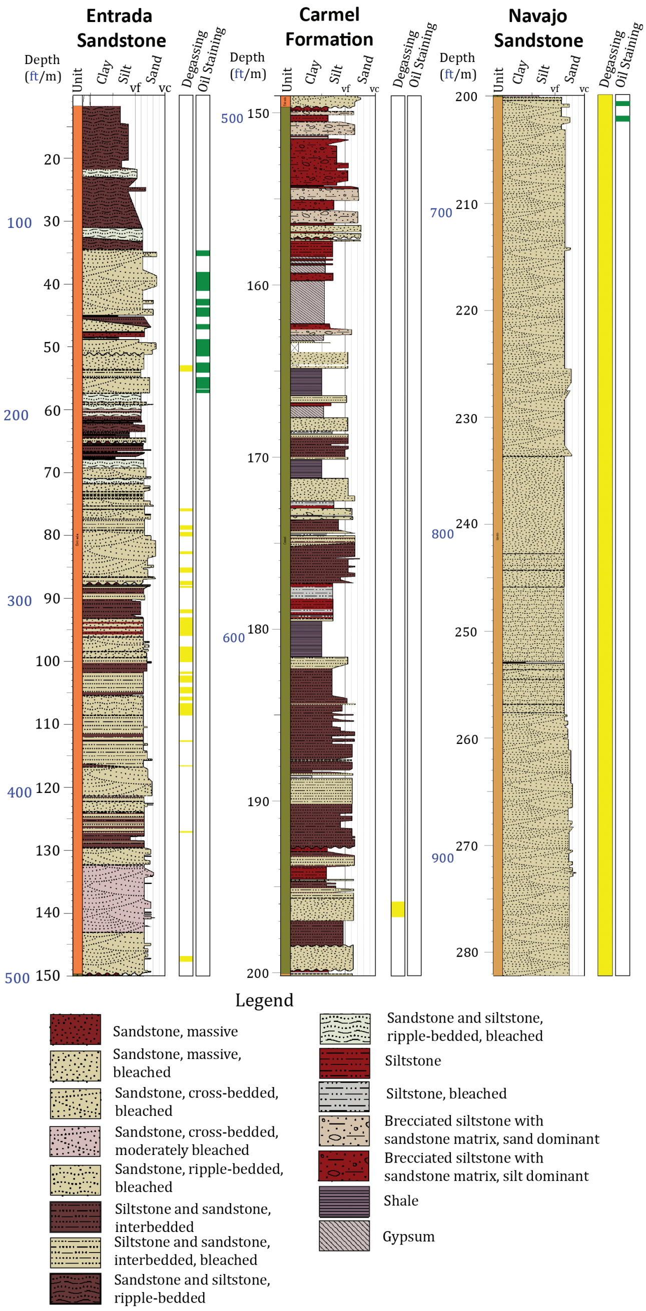

Figure 5. Sedimentary log of the core recovered from drill hole CO2W55 showing the main geological features of the three units, the Entrada Sandstone, Carmel Formation and Navajo Sandstone, transacted by the drill hole. Zones of CO_2-degassing core and hydrocarbon bearing zones are also shown.

Such sandstone bleaching is a common feature within the Jurassic sandstones of the Paradox Basin and wider geographic region. This has variously been attributed to bleaching by buoyant hydrocarbons and methane rich brine (Beitler et al., 2003, 2005; Chan et al., 2000; Garden et al., 2001; Parry et al., 2004, 2009) and by dense CO_2-charged brine containing methane or sulfide reductants (Loope et al., 2010, 2011; Potter-McIntyre et al., 2013; Wigley et al., 2012,

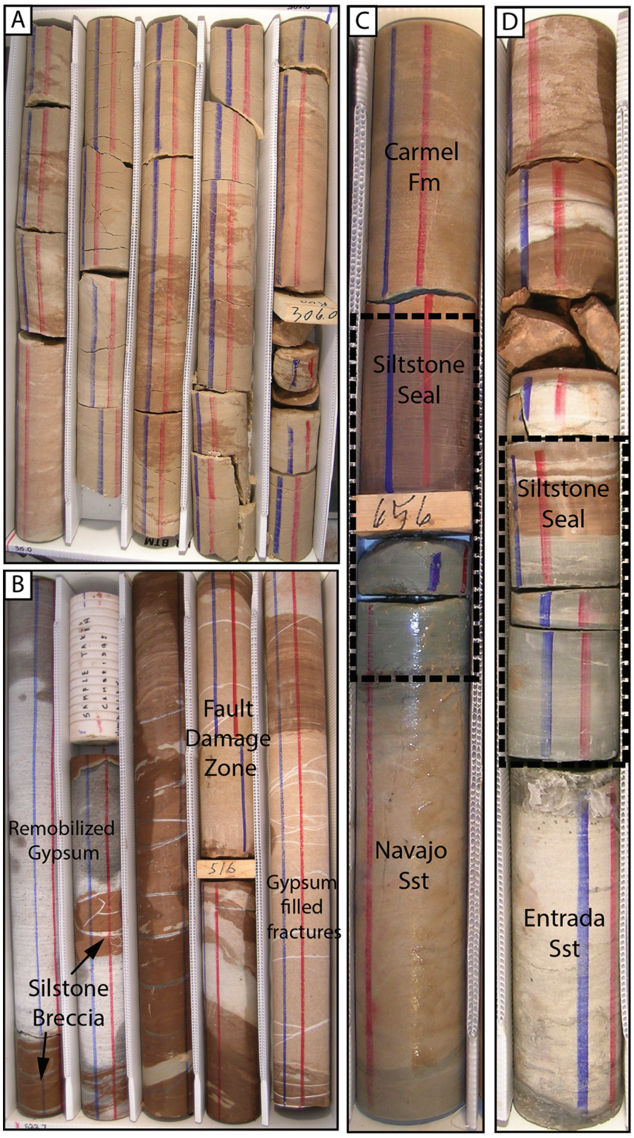

Figure 6. **(A)** Bleached basal sandstones of the Entrada Sandstone hosting CO_2 charged fluids. Fracturing of the core occurs at surface due to exsolution of CO_2 gas from the fluids held in core porosity. The relative permeabilities of water and gas result in a build-up of gas within the pore space, which expands causing the cores to break apart. **(B)** Sections of the fault core and damage zone from the Carmel formation showing fractured blocks of siltstone residing in remobilized gypsum horizons and pervasive fracturing of the core in the footwall fault damage zone. **(C)** and **(D)** Siltstone-sandstone contacts from CO_2-hosting sections of the Entrada and Navajo Sandstones showing bleaching and alteration of the originally red siltstones over a 10 cm distance by diffusion of volatiles into the reservoir cap rocks.

2013a, 2013b). Ferric iron bearing hematite is relatively insoluble in water at low temperatures and its dissolution requires a source of acidity and a chemical agent to reduce insoluble Fe^{3+} to soluble Fe^{2+}. Such acid-reductive dissolution is possible with a wide range of naturally occurring sources of acidity (e.g. CO_2, organic acids, H_2S) and reductants (e.g. CH_4, HS^-, H_2S) and different combinations most likely act as the bleaching agent in different places. At Green River bleaching of exhumed portions of the Entrada Sandstone has previously been attributed to the passage of CO_2-charged brine, with minor quantities of dissolved CH_4. The presence of these CO_2-rich brine has been inferred from analysis of CO_2-CH_4 bearing fluid inclusions within secondary mineral phases and the isotopic composition of secondary carbonate cements associated with the bleaching (Wigley et al., 2012, 2013b). In addition, bleached portions of the exhumed Entrada studied by Wigley et al. (2012, 2013a, b) contain assemblages of gypsum and pyrite in open fractures, although the pyrite is rarely preserved (typically as inclusions within gypsum) due to oxidative weathering at the surface. Such assemblages are more commonly preserved within the CO2W55 core as fracture coatings around intensely bleached open fractures in the Navajo and Entrada Sandstones. At Green River the sandstone bleaching may occur through a series of linked reactions involving a range of reduced species following reaction stoichiometries such as

$$4Fe_2O_3+15CO_2+6H_2O+CH_4 \rightarrow 8Fe^{2+}+16HCO_3^- \qquad (R1)$$

$$Fe_2O_3+4CO_2+H_2O+2HS^- \rightarrow Fe^{2+}+4HCO_3^- + FeS_2. \qquad (R2)$$

Mineralogical, petrographic and isotopic analysis of the bleach units and bleaching related mineral assemblages will form a focus of future analyses. The lower portions (5–10 cm) of many of the sealing siltstone layers in the Entrada and Carmel formations are also bleached where they are in contact with CO_2-hosting reservoir sandstones, suggesting upwards penetration of volatiles by diffusion, mineral dissolution and alteration of the cap rock mineralogy.

7 Fluid sampling results

Initial results of the downhole and surface fluid sampling results are presented in Fig. 7, full details of the fluid geochemical analyses and results can be found in Kampman et al. (2013b). The Na^+ and Cl^- concentrations of the fluids are fairly constant through the Entrada Sandstone, the fault damage zone in the Carmel and in the upper Navajo Sandstone (Fig. 7a–b). Within the Navajo Sandstone Na^+ and Cl^- concentrations increase systematically towards the base of the formation, and this broad salinity profile reflects mixing between dense brine flowing along the base of the formation, fed by active inflow from the main fault zone, and dilute meteoric fluid flowing horizontally into the fault. Dissolved CO_2 concentrations in the Navajo Sandstone determined by titration of "alkalinity captured" samples and calculated from the measured in situ pH and fluid alkalinity (Fig. 7c) are in good agreement (Fig. 7d). CO_2 concentrations are close

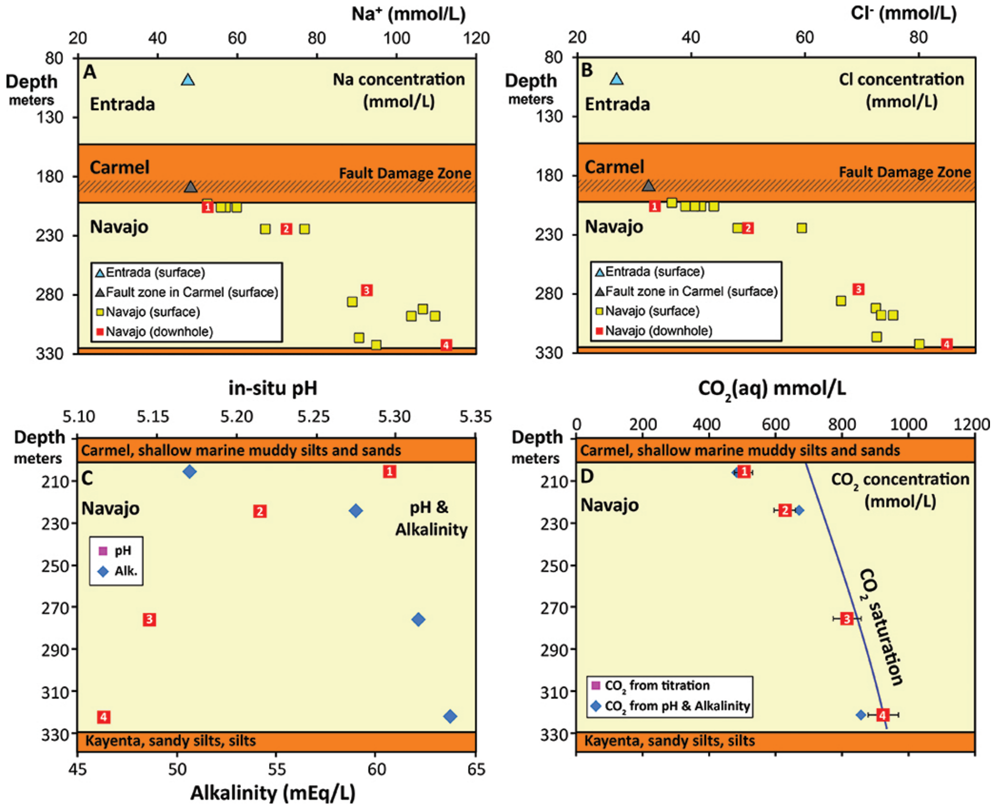

Figure 7. Preliminary results from the surface and downhole fluid sampling campaign. **(A–B)** Na^+ and Cl^- concentrations in downhole and surface sampled fluids. The geochemical profiles illustrate inflow of CO_2-charged brine at base of the formation and mixing between brine flowing through the faults and meteoric fluid flowing horizontally into the fault zone. **(C)** In situ pH measured on pressurized samples and alkalinity determined by Gran titration in the field. **(D)** Dissolved CO_2 concentrations measured directly on titrated samples and recalculated from measured pH and alkalinity. Also shown is the theoretical CO_2 solubility curved calculated for a hydrostatic pressure gradient, local geothermal gradient and measured salinity profile using the equations of Duan et al. (2006).

to saturation at the base of the formation and decrease upwards due to mixing between the CO_2-saturated brine and CO_2-undersaturated meteoric fluid higher in the formation. These results suggest that the Navajo Sandstone is being fed by active inflow of CO_2-saturated brine through the damage zone of the main Little Grand Wash Fault, and that the fluid sampling successfully captures this dynamic process.

8 Conclusions

For the first time, core of a cap rock/reservoir pair and accompanying downhole fluid samples from a naturally CO_2-charged reservoir have been obtained. Surface and downhole fluid sampling reveals that the sandstone formations are being fed by active inflow of CO_2-saturated brine through fault fracture networks; with the CO_2-charged brine being sourced from supercritical reservoirs of CO_2 at depth within the basin. The sandstone and siltstone units are bleached from their typical red colour where they are in contact with the CO_2-charged fluids. Narrow zones of mineralogical alteration are observed in the cap rock units in contact with the CO_2-charged reservoir sandstones.

Forthcoming analysis will include mineralogical, petrographic, geochemical and geomechanical studies of the CO_2-reservoir rocks and reservoir cap rocks. Geochemical, mineralogical and petrophysical profiles through the cap rocks will be combined with diffusive modelling to constrain the velocity of the mineral reaction fronts. This work aims to establish whether CO_2-promoted fluid–mineral reactions have occurred in the cap rocks and if these reactions either (i) attenuate the CO_2 diffusive distances through the consumption of the CO_2 and the deposition of carbonate minerals or (ii) facilitate CO_2 escape by generating porosity and permeability pathways. The results of this analytical work will be compared to, and used to calibrate, numerical models of coupled CO_2–fluid–mineral reactions. Further drilling is planned at the Green River site to target fault zones that host CO_2 and CO_2-charged fluid flow. Core samples obtained from this drilling will be studied in order to assess the impacts of CO_2-promoted fluid–rock interaction on fracture permeability, fault hosted fluid flow and surface leakage of the CO_2.

Scientists of the Green River Drilling Project (GRDP)

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Scientific Drilling
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Establishment of the Coast Range ophiolite microbial observatory (CROMO): drilling objectives and preliminary outcomes

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Abstract. This project aimed to establish a subsurface microbial observatory in ultramafic rocks, by drilling into an actively serpentinizing peridotite body, characterizing cored rocks, and outfitting the boreholes for a program of long-term observation and experimentation to resolve the serpentinite-hosted subsurface biosphere. We completed drilling in August 2011, drilling two boreholes with core recovery and possibility for down-hole experimentation, and six smaller-diameter monitoring wells arrayed around the two primary holes, in the Coast Range ophiolite (CRO) locality in the UC-Davis McLaughlin Natural Reserve, Lower Lake, CA. Every effort was made during drilling to keep the cores and wells as free of drilling-induced contamination as possible: clean, purified water was used as drilling fluid, fluorescent microbead tracers were suspended in that water for quantification of drilling fluid penetration into the cores, and high resolution next generation sequencing approaches were used to characterize the microbial populations in the drill fluids and core materials. In December 2011, we completed installation of well pumps (slow flow bladder pumps) in the monitoring wells, and have deployed a set of in situ incubation experiments in the two uncased boreholes. Preliminary findings illustrate natural variability in actively serpentinizing strata, and confirm distinct groundwater flow regimes and microbial ecosystems in (a) shallow, surface-impacted soil water horizons and (b) deeper, ultramafic bedrock-sourced formation fluids.

1 Introduction and goals/scientific objectives

Background

Serpentinites have been the target of numerous deep-sea drilling expeditions over the years, including expeditions to Hess Deep and along the Mid-Atlantic Ridge (e.g., Mével et al., 1996; Karson et al., 1997; Kelemen et al., 2007). Historically, these expeditions were in large part motivated by exploration of the structural, petrologic, and tectonic evolution of the ocean crust. The discovery of the Lost City hydrothermal field (Kelley et al., 2001, 2005) stimulated increasing interest in the capacity of serpentinites to support biological communities, both at and below the seafloor (Schrenk et al., 2013). Recently, interest in the biological potential of serpentinites has begun to extend into the continental realm, leading to the initiation of efforts to drill into serpentinites on land to investigate biological activities that may be occurring beneath the surface. Here, we report on the establishment of a subsurface microbial observatory within an active serpentinite in the California Coast Range.

Serpentinization is a pervasive process in many geologic terranes, however the geochemical processes, rates, and their relationship to microbiology are very poorly constrained.

The life-supporting potential of serpentinites has been discussed at length (Shock, 1997; Nealson, 1997; Fisk and Giovannoni, 1999; Sleep et al., 2004; Nealson et al., 2005; Schulte et al., 2006; McCollom, 2007; Schrenk et al., 2013), and experimental work has constrained controls on H_2 and CH_4 generation (Berndt et al., 1996; McCollom and Seewald, 2001; Allen and Seyfried Jr., 2003; Seyfried Jr. et al., 2007). Field-based studies of both fluid discharge sites (Kelley et al., 2001, 2005; Takai et al., 2004; Schrenk et al., 2004) and serpentinized rocks (Alt and Shanks III, 1998; Alt et al., 2007; Schulte et al., 2006) have drawn some boundaries on modern examples of ongoing serpentinization and available bioenergetic resources. Also relevant are the many studies focused on the production of abiotic organic molecules in serpentinites, and possible supply of prebiotic molecules to planetary systems (cf., Shock and Schulte, 1998; Holm and Andersson, 1998; Martin and Russell, 2007; Proskurowski et al., 2008).

In the presence of water at temperatures and pressures characteristic of earth's surface or near-surface environments, olivine in ultramafic igneous rocks alters to serpentine minerals (e.g., lizardite, chrysotile, and antigorite), hydroxides, and magnetite (Moody, 1976; Früh-Green et al., 2004), increasing alkalinity, as shown in by the general reaction:

$$\underset{\text{Olivine}}{(\mathrm{Mg,Fe})_2\mathrm{SiO}_4} + \mathrm{H_2O} \rightarrow \underset{\text{Serpentine}}{(\mathrm{Mg,Fe})_3\mathrm{Si_2O_5(OH)_4}} \tag{R1}$$

$$+\underset{\text{Brucite}}{(\mathrm{Mg,Fe})(\mathrm{OH})_2} + \underset{\text{Magnetite.}}{\mathrm{Fe_3O_4}} + \mathrm{H_2}$$

The stoichiometry of the reaction as well as the compositions of product phases are dependent on a number of factors including temperature, initial rock and mineral compositions, and fluid : rock ratio (e.g., Klein et al., 2009). The H_2 is produced through oxidation of ferrous iron by water to ferric iron [Fe(III)], which typically precipitates as magnetite. The process can be represented by the expression:

$$2(\mathrm{FeO})_{\mathrm{rock}} + \mathrm{H_2O} \rightarrow (\mathrm{Fe_2O_3})_{\mathrm{rock}} + \mathrm{H_2}, \tag{R2}$$

where $(FeO)_{rock}$ refers to the ferrous component of igneous silicate minerals and $(Fe_2O_3)_{rock}$ refers to the ferric component of Fe-bearing mineral alteration products, such as magnetite.

Thus, mineral transformations associated with serpentinization can produce significant quantities of H_2, a widely utilized source of energy for micro-organisms, and might thereby fuel an attendant biosphere (Nealson et al., 2005). At the same time, serpentinization at low temperatures ($< \sim 250\,^{\circ}C$) can drive the pH of ambient waters to levels sometimes in excess of 12 (more alkaline than household ammonia), which may both tax microbial communities and also sequester the inorganic carbon required for metabolism or biosynthesis. The balance of these factors in creating habitable conditions is only beginning to be understood. Additionally, the reactions presented above are idealized; the stoichiometry and rates of production of H_2 and hydroxides (along with the postulated potential for hydrocarbon production) depend significantly on the starting composition of rocks and reactive fluids as well as pressure-temperature-composition conditions. We are thus faced with the problem of extrapolating the habitability of serpentinizing systems, across a broad range of conditions, from a few "point observations".

The most comprehensive geobiological characterization of a submarine serpentinizing system thus far published is for the Lost City Hydrothermal Field, ~ 15 km off the Mid-Atlantic Ridge. Here, venting fluids sourced in serpentinizing host rock exhibit extreme enrichment in both alkalinity (pH of 9–11), and dissolved H_2 (15 mM), along with abundant dissolved methane (2 mM) (Kelley et al., 2005). The site also hosts a microbial food web apparently dependent on the chemical disequilibrium furnished by mixing of serpentinizing fluids with deep sea water (McCollom, 2007; Brazelton et al., 2006; Schrenk et al., 2004; Kelley et al., 2001, 2005).

On land, serpentinizing fluids may be harder to locate, as they may have more moderate chemistries (less extreme pH, with or without observable gas inventory) and are trapped within weathering bodies of rock, representing a lower energy environment that may yet persist over geologic time. Fluid circulation may be slower than in submarine settings, without vigorous hydrothermal circulation driven by hot young oceanic crust. Where these fluids find surface expression, the reaction of serpentine seep fluids with our atmosphere produces notable mineralization: serpentinizing waters escaping The Cedars peridotite body in Sonoma county (Morrill et al., 2013; Suzuki et al., 2013) produce undulating travertine ($CaCO_3$) terraces at the outflow points of subsurface springs, and the geologically similar Complexion Spring site (Schulte et al., 2006) has a pool of striking white sediment (fine grained serpentine phases with diverse salts, suggested by early description in Bradley (1915) and aqueous geochemistry in Goff et al., 2001). High pH springs sourced in ultramafic units of the Oman ophiolite are also under close study, with extremely low dissolved inorganic carbon (20 to 380 $\mu mol\,L^{-1}$), pH values up to 11.9, and oxidation-reduction potential as low as -611 mV, indicating a strongly reducing subsurface environment (Paukert et al., 2012). The few geomicrobiological studies conducted so far have been primarily limited to sites of subaerial fluid discharge. Within the serpentinites themselves, conditions for potential life can be expected to be very different. Additionally, the microbial ecology of sites in contact with earth's surface and atmosphere likely depend on oxygen – in the more reducing subsurface, microbes need strategies to oxidize hydrogen with other electron acceptors, a very different challenge. Recent work at the Tablelands Ophiolite in Newfoundland, Canada, has begun to clearly demonstrate the relationships between ultrabasic fluids and volatile gases associated with serpentinization and the microbial communities they support (Brazelton et al., 2012, 2013). Although the serpentinite-sourced origin of venting fluids at such sites seems to have been clearly established, relatively little is yet published in regard to any associated biological communities. These results are consistent with finding from a deep ultrabasic wells at Cabeço de Vide in Portugal, studied by Tiago and colleagues, demonstrating a high abundance of gene sequences related to anaerobic, hydrogen metabolizing microbial taxa (Tiago and Veríssimo).

Current understanding of the habitability of subsurface serpentinizing systems has been missing a critical component: the comprehensive investigation of a site where ongoing, low temperature serpentinization can be monitored in situ, and in particular, near the site of serpentinization, where it can be monitored directly in the subsurface. This is of primary importance in assessing the natural range of habitats created by serpentinization. Drilling at the Coast Range ophiolite microbial observatory (CROMO) recovered intact rock and sediment samples directly from the serpentinizing subsurface. The successful establishment of the CROMO at Lower Lake, CA (in the McLaughlin Natural Reserve), administered by the University of California-Davis, has allowed characterization, comprehensively and over time, of the geology, geochemistry, and biology associated with serpentinization in situ in the sub-surface.

The project's overarching goal is to understand how serpentinization affects subsurface habitability. We have taken an important first step toward this longer term goal, by establishing a subsurface observatory in an actively serpentinizing body, and conducting an initial suite of integrated characterization. Specific objectives were to

1. Characterize the mineralogy and geochemistry accompanying active serpentinization, with particular emphasis on constraining the processes that may impact habitability most directly (e.g., provision of geochemical energy sources, alteration of fluid chemistry in ways supportive or detrimental to life).
2. Establish a suite of dedicated boreholes in an actively serpentinizing body, and instrument those boreholes to allow for frequent monitoring of the parameters affecting habitability at specific depths.
3. Characterize any microbial communities that may be present in the cored materials, in the associated groundwater, or that may develop within the borehole during the monitoring period.
4. Evaluate how the geochemical environment may support (or not) photosynthesis-independent subsurface life, placing particular emphasis on energy availability, challenges posed by highly alkaline or otherwise toxic conditions, and availability of carbon and micronutrients.
5. Investigate whether organic compounds are present that are indicative of abiotic synthesis pathways or serve as biomarkers of the biological community.

2 Geologic and microbiological settings

General site description

In northern California, the Coast Ranges stretch north ~ 600 km from the Golden Gate Bridge in San Francisco, in an area bounded loosely by the Pacific Ocean to the west, the Coast Range of Oregon and Washington to the north, the Klamath Mountains to the NE, the Great Valley of California to the SE, and the drainage of the Sacramento and San Joaquin rivers to the south (Alexander et al., 2006). Serpentine soils occur throughout this region, with distinctive vegetation and ecology, all dependent on the subaerial weathering of ultramafic bedrock, specifically, olivine and pyroxene minerals in peridotite. Blocks of the CRO, equivalent to Jurassic ocean crust tectonically emplaced on land, are reacting with trapped Cretaceous seawater in this region (Peters, 1993; Shervais et al., 2005) and may be experiencing also some degree of meteoric inputs (Peters, 1993).

Historical and new data for ultramafic-hosted groundwater monitoring wells were made available for expedition planning by the Homestake Mining Co., Inc., which completed regional exploration drilling for conducting gold mining in the vicinity. Homestake records indicate a hydrologic flow system characterized by elevated pH, high dissolved Cr and high Ca / Mg ratios, and higher than expected dissolved H_2 and CH_4. The Homestake wells were created as environmental monitoring wells, without the purpose of monitoring microbiology or organic geochemistry. A project was planned to drill a set of dedicated scientific groundwater monitoring wells, limiting potential microbial contamination, in order to make CRO formation fluids accessible, at the McLaughlin Natural Reserve (Fig. 1), a University of California at Davis-administered research and educational reserve, in Lower Lake, CA.

3 Drilling strategy/field operations

Cascade Drilling successfully completed the required drilling tasks despite the challenging condition of using only purified water as a drilling fluid. Coring was accomplished using a Central Mine Equipment Company (CME) Model 75 auger rig, running rods down with auto-hammer (140 lbs, 30 inch stroke). This was HQ coring; HQ indicates a wireline bit size with an outer diameter of 96 mm and an inner diameter of 63.5 mm. For the rapid installation of remaining water monitoring wells, 8-inch CME hollow stem augers were used, without core retrieval. In all, 37 800 gallons (143 088 L) of water were provided by the Ice Water Company, Lower Lake, CA, for use during drilling; all water had passed

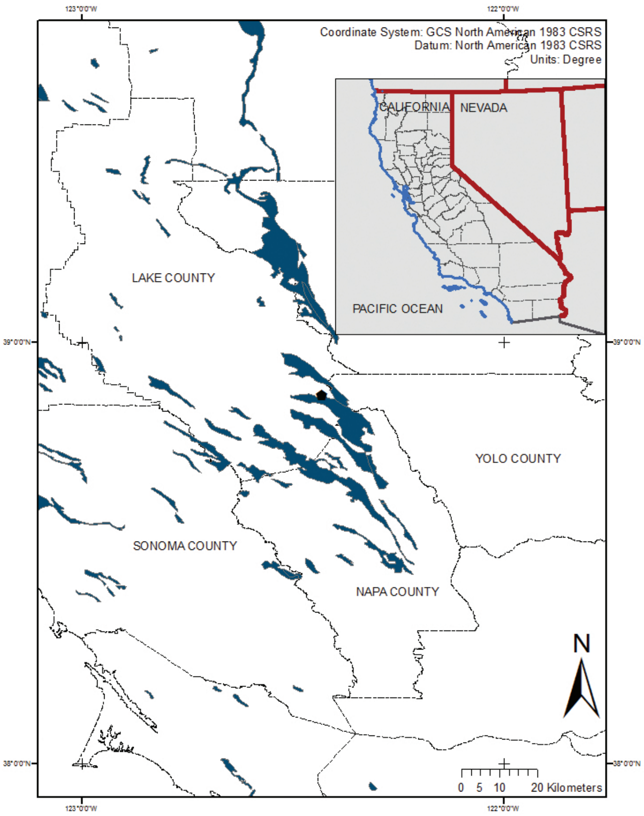

Figure 1. County map of California overlain with serpentinite units colored steel blue in ArcMap10, derived from USGS georeferenced geologic map data (USGS OFR 2005-1305). Drilling took place in Lower Lake, CA in the boundaries of the McLaughlin Natural Reserve, administered by the University of California at Davis, Lower Lake, CA; this site is shown as a black hexagon near the center of map.

through 1 micron filters and ozonated prior to delivery (Supplement Table S1 for certificate of analysis).

No additional muds/lubricants were applied. We added fluorescent 0.5 µm polystyrene spheres (Polysciences Inc.) at a concentration of approximately 10^4 beads per mL of ingoing water to track the movement of microorganism-sized particles through the core material. We utilized best practices developed during biology-themed deep sea drilling investigations, monitoring the penetration of fluorescent microspheres in cores (Smith et al., 2000a, b; House et al., 2003) to track drilling-related contamination of cores. Subsections from both the exterior of the samples and interior to the whole round cores were sequentially washed with sterilized phosphate buffer saline solution, and used to monitor the presence of microspheres. Only those samples free of microsphere contamination were used in subsequent microbiological analyses.

A total of eight wells were emplaced (Table S1 for well monument coordinates). Two primary wells were drilled, from which cores were retrieved, and cased only to bedrock – leaving the bottom of hole (BOH) uncased. Current depths of wells are as follows. The up-valley primary well is QV1,1 (to 23 m depth); shallower (QV1,2 was drilled 2.2 m east of QV1,1 to 14.9 m depth) and deeper (QV1,3 was drilled 2.1 m east of QV1,2 to 34.6 m depth) wells were drilled as close to this priority hole as drilling conditions permitted. The down-valley primary well is CSW1,1 (to 19.5 m depth); shallower (CSW1,4 was drilled 14.7 m north of CSW1,1 to 8.8 m depth), roughly equivalent depth (CSW1,2 was drilled 11.7 m east of CSW1,1 to 19.2 m depth, and CSW1,3 was drilled 11.9 m west of CSW1,1 to 23.2 m depth), and deeper (CSW1,5 was drilled 9.4 m south of CSW1,1 to 27.4 m depth) wells were drilled in a diamond-shaped array around to CSW1,1. Core recovery observations for the primary wells are as follows. Both primary sites had problems with partial hole collapse upon withdrawal of the drilling tools: driller's depth for QV1,1 was 45.72 m, but current BOH as determined by logging is 30 m; driller's depth for CSW1,1 was 31.1 m, but current BOH is 19.5 m as determined by logging.

Based on the computation of (100 × total recovered core length)/total cored depth = % core recovery, % core recovery for holes QV1,1 and CSW1,1 is taken as 64 % and 46 %, respectively. The better core recovery for the QV1,1 site is likely due to the combination of cautious augering followed by coring with the California-Modified Style Split-Spoon Sampler (on a safety driver winch with a 140 lb down-hole hammer with a 30 in. stroke), which may be successfully sent through hollow-stem auger borings or direct push tooling, in a generally competent ultramafic block. Though the same drilling strategy was utilized at CSW1,1, the much lower core recovery for this site is likely due to interception of fractured, fine-grained serpentinite in serpentine-dominated clay matrix; much of this material was lost during core retrieval.

Rock cores were curated in a fashion modeled after IODP (Integrated Ocean Drilling Program) best practices. Following photo-documentation and preliminary core description, cores were sampled from combusted aluminum foil sections on the description table and preserved as required for complementary geochemical, microbiological, and organic geochemical analyses within 30 min of collection. Specified whole round core samples have been archived for geomicrobiology, frozen in liquid nitrogen following collection and maintained at –80 °C other than during shipping and freezer transfer to laboratories at East Carolina University-Biological Sciences (Schrenk) and University of Rhode Island-Geosciences (Cardace). Remaining cores are maintained in the University of Rhode Island-Geosciences (Cardace) in conventional storage boxes. Requests to subsample cores will be considered on a case by case basis; existing research management infrastructure at McLaughlin requires research permit application, and the project investigators (Cardace, Hoehler, McCollom, and Schrenk) serve as a committee to facilitate research access to cores and wells.

4 Preliminary scientific results

4.1 Mineralogy and geochemistry

A Terra (distributed by Olympus, formerly InXitu) portable X-ray diffractometer is used for XRD analysis of mineral phases. Standard operating procedures engage a Co X-ray source and a cooled charge-coupled device (CCD) detector arranged in transmission geometry with the sample, with an angular range of 5 to 50° 2θ with $< 0.35°$ 2θ resolution (Blake et al., 2012). X-ray tube voltage is typically 30 kV, with a power of 10 W, a step size of 0.05°, and an exposure time of 10 s per step. Total run time is set at 1000 exposures, requiring about 75 min run time.

XRD samples are powdered using a percussion mortar and agate mortar and pestle; when necessary a Dremel manual drill was used to subsample grains of interest. Powders are passed through a standard 150 µm sieve (or 100-mesh). About 15 mg of powdered material is transferred with a spatula to the inlet hopper of the standard sample vibration chamber, which continuously mixes the powdered sample for the duration of the analysis. Interpretation of diffractograms is conducted using XPowder software, which is a commercially available search and match program that queries the PDF2 database for reference mineral peak information.

Once prepared, sample powders are subjected also to bulk XRF analysis by benchtop XRF (Niton XL3T 600) run in atmospheric data collection mode, appropriate for preliminary screening of the geochemistry of bulk soils and sediments according to the EPA 6200 method (US-EPA, 2007); accuracy for analytes Zr, Sr, Rb, Pb, As, Zn, W, Cu, Fe, Mn, Cr, V, Ti and S was confirmed by comparison of results for standard reference material TILL-4, a Natural Resources Canada product; for these analytes, a best-fit line for data on a plot of observed vs. reference data proved to have a $R^2 = 0.99966$. Precision was assessed by triplicate analyses of each sample, symbols encompass absolute uncertainty. A more comprehensive analytical data set (via ICP-MS) is in process, but data for Sr, Rb, Fe, Mn, Cr, V, and Ti are shared as a Supplement with this report.

Cores comprise pervasively altered peridotite with relic primary minerals olivine/pyroxene, diverse secondary phases including serpentine, magnetite, carbonates, and mixed clays, including chlorite. X-ray diffraction (XRD) data (Fig. 6, Table S2) indicate three main mineral assemblages: (1) a shallow, weathered zone assemblage (Fig. 6, top panel), (2) a serpentine-dominated assemblage (that may also be chlorite-bearing, Fig. 6, middle panel), and (3) an albite-bearing assemblage suggestive of mafic rock alteration, likely of a gabbroic body (Fig. 6, bottom panel).

Thin section petrography confirms the broad findings of the XRD results. Figure 7 presents both a representative thin section of a lizardite-rich sample (this variety of serpentine dominates low-temperature serpentinization processes) and

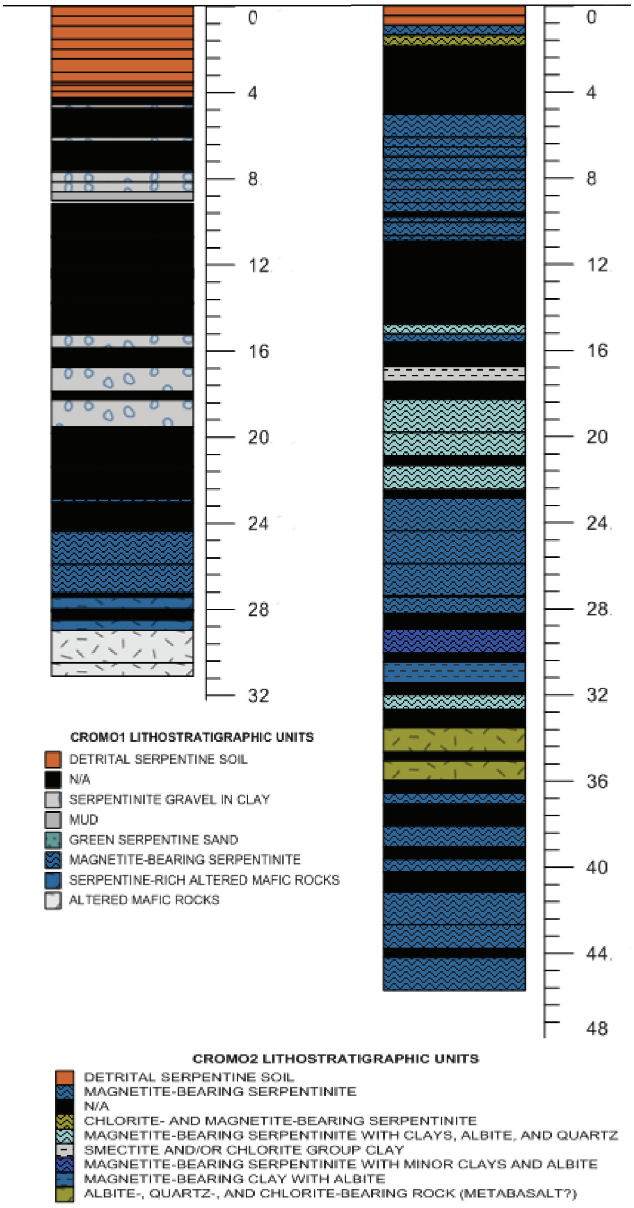

Figure 2. Lithostratigraphic summaries of CROMO1 and CROMO2. Left: CROMO1, the Core Shed area well, was drilled at 38°51.711′ N, 122°24.856′ W, and is in a grassy flat with low shrubs and a few introduced trees. Reddish altered peridotite blocks are upslope of the site, with green-blue scrapes showing fresher serpentinite where soil cover has eroded. A few meters of soil was underlain by bedrock. B.O.H. was at a depth of 45 m. Post-drilling measurement of pH in the uncased borehole gave a pH of 11.4. Right: CROMO2, the Quarry Valley well, was drilled at 38°51.724′ N, 122°25.827′ W, and is characterized by serpentine meadows, steep slopes with altered peridotite outcrops. A few meters of soil graded into less altered material and finally bedrock. Bottom of hole (B.O.H.) was at a depth of 31 m. Post-drilling measurement of pH in the uncased borehole gave a pH of 12.5.

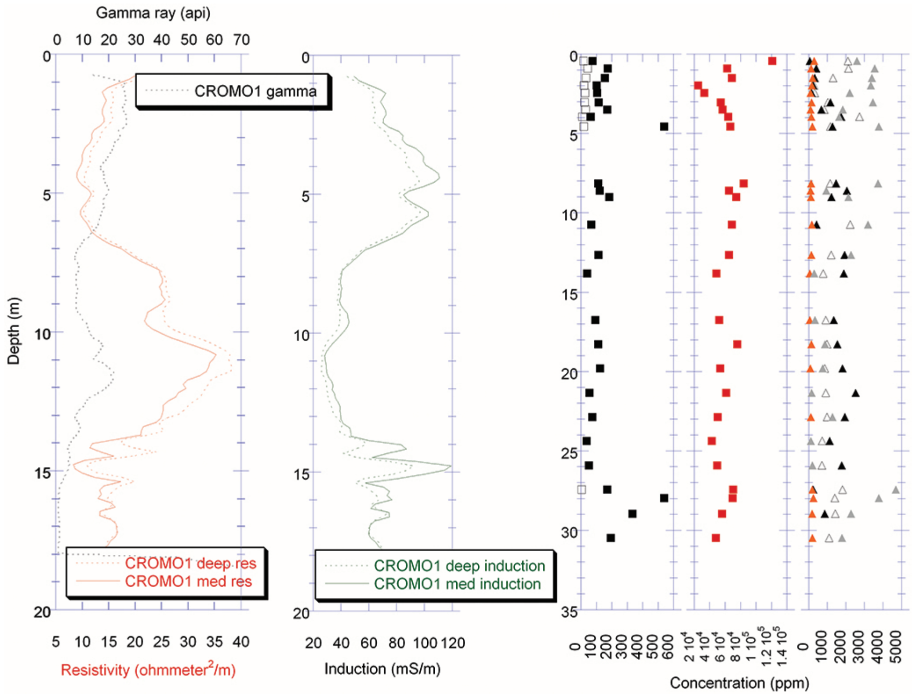

Figure 3. Geophysical logging results (temperature, gamma, induction, resistivity logs) for CROMO1, drilled near the Homestake Mining Inc. Core Shed at the McLaughlin Natural Reserve. In all plots, depth is plotted along the *y* axis, as meters below surface. Leftmost panel: this depth profile shows variation in gamma ray signal in units of api; U, Th, K-concentrating lithologic units drive values up. Also shown are observed resistivity data in units of $\Omega m^2 m^{-1}$; medium resistivity conveys information about resistivity near tool, while deep resistivity conveys information about resistivity far from tool in the surrounding formation. Left-middle panel: this depth profile shows observed induction in units of mSiemens m^{-1}, a measure of induced electrical field in formation rocks; medium induction conveys information about conductivity near tool, while deep induction conveys information about conductivity far from tool. Right trio of panels: bulk powder XRF geochemical data for selected analytes (Sr, Rb, Fe, Mn, Cr, V, Ti) are shown in a trio of plots; Sr data are filled squares, Rb data are open squares, Fe data are red squares, Mn data are open triangles, Cr data are black triangles, V data are brown triangles, and Ti data are gray triangles.

an example of the albitic alteration digesting plagioclase (a characteristic alteration pattern in mafic rocks).

4.2 Lithostratigraphy

The first borehole (Fig. 5, left) was drilled in the Quarry Valley area of the McLaughlin Natural Reserve. This area is characterized by a valley bottom comprising riparian vegetation, valley oak (*Quercus lobata*) woodland, and adjacent meadows supporting a mixture of serpentine-tolerant and serpentine intolerant herbaceous vegetation, flanked by fairly steep slopes with reddish altered peridotite, gabbro, sedimentary rock outcrops or blocks supporting a mosaic of variable chaparral shrub-lands and blue-oak woodland. We encountered a few meters of soil, grading into lesser altered material and finally bedrock. Bottom of hole (B.O.H.) was originally at a depth of 45.72 m; the hole collapsed partially upon removal of rig to 23 m. Post-drilling measurement of groundwater pH in the uncased borehole gave a pH of 12.5.

The second borehole (Fig. 5, right) was drilled in the Core Shed area of the McLaughlin Natural Reserve. This area is characterized by a valley bottom comprising riparian vegetation, valley oak (*Quercus lobata*) woodland with some introduced trees planted by homesteaders, and adjacent meadows supporting a mosaic of serpentine-tolerant and serpentine-intolerant herbaceous vegetation. The location is flanked by slopes with reddish altered peridotite blocks, and green-blue scrapes showing fresher (i.e., less oxidized by surface weathering) serpentinite where the soil cover has eroded, and supporting serpentine chaparral. Here we encountered a few meters of soil, underlain by bedrock. B.O.H. was at a depth of 31.09 m; the deepest part of the hole caved in upon removal of the rig to 19.5 m. Post-drilling measurement of groundwater pH in the uncased borehole gave a pH of 11.4.

4.3 Logging

Basic geophysical logging following installation of PVC casing was conducted (with Welenco Inc., D. Ihde http://www.welenco.com) as soon as feasible following drilling, between 11 and 16 August 2011. Temperature data were logged in °C, collected with semiconductor temperature

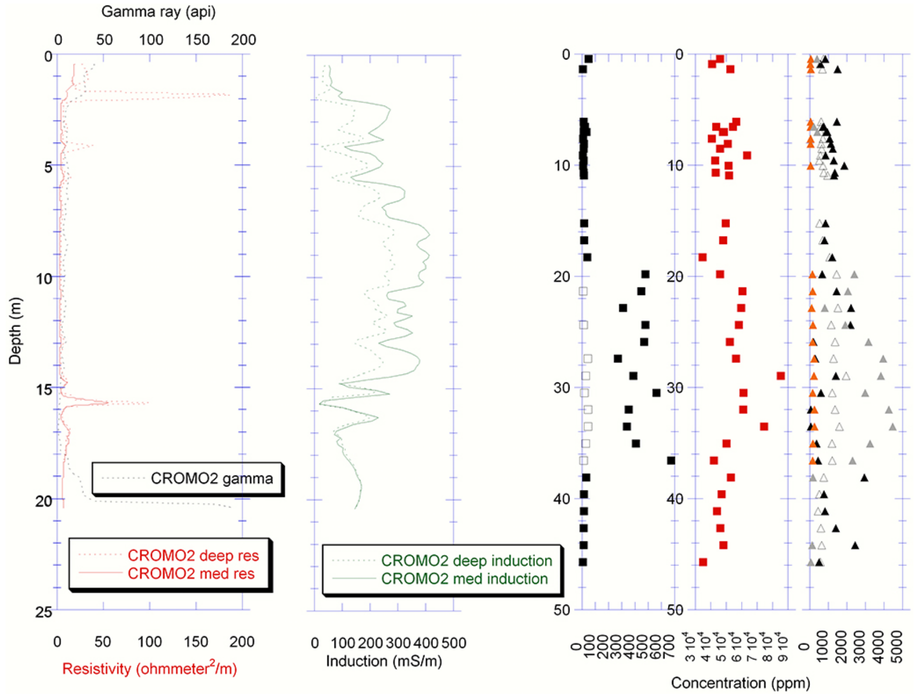

Figure 4. Geophysical logging results (temperature, gamma, induction, resistivity logs) for CROMO2, drilled about 1 km west of CROMO1, in the Quarry Valley area at the McLaughlin Natural Reserve. In all plots, depth is plotted along the *y* axis, as meters below surface. Leftmost panel: this depth profile shows variation in gamma ray signal in units of api; U, Th, K-concentrating lithologic units drive values up. Also shown are observed resistivity data in units of $\Omega m^2\,m^{-1}$; medium resistivity conveys information about resistivity near tool, while deep resistivity conveys information about resistivity far from tool in the surrounding formation. Left-middle panel: this depth profile shows observed induction in units of mSiemens m^{-1}, a measure of induced electrical field in formation rocks; medium induction conveys information about conductivity near tool, while deep induction conveys information about conductivity far from tool. Right trio of panels: bulk powder XRF geochemical data for selected analytes (Sr, Rb, Fe, Mn, Cr, V, Ti) are shown in a trio of plots; Sr data are filled squares, Rb data open squares, Fe data red squares, Mn data open triangles, Cr data black triangles, V data brown triangles, and Ti data gray triangles. Numerical data presented in Supplement Table S3.

sensor (Robertson Geologging Borehole Logging System temperature/conductivity sonde, model I002055; rated for range of 0 to 70 °C); for CROMO1 and CROMO2, logging data stabilize at 14.5 °C at 13 m depth and 15.3 °C at 15 m depth, respectively. This is a reasonable shallow groundwater temperature for the area. Temperature data do not show any pronounced excursions, which could indicate through-going hydrological flow.

The Dual Focused Induction Sonde (Robertson Geologging Borehole Logging System dual focused induction probe with natural gamma, model I002087; rated for range of 200 to 10 000 mS m^{-1}) measures natural gamma ray and conductivity of surrounding formations, by monitoring the response of an induced electrical current to local conditions. Figure 3 (for CROMO1, drilled at the Homestake Core Shed area) and Fig. 4 (CROMO2, drilled at western edge of Quarry Valley area) show logging data organized by borehole, with selected geochemical parameters as discussed above. Notice that gamma ray intensity varies from near zero to ~ 50 api at CROMO1 (Fig. 3), while it varies from near zero to ~ 200 api at CROMO2 (Fig. 4), suggesting variability in lithologic units across the ~ 1 km distance between drilling sites. Induction data (also in Figs. 3 and 4) reflect the conductivity of the tested formation; higher total dissolved solids in a solution results in lower resistivity and higher conductivity, given the inverse mathematical relation of the two terms. As shown, in Fig. 3 at CROMO1, there is a concurrent low induction and high resistivity zone from about 8 to 12 m below surface, indicating a zone of decreased total dissolved solids. At CROMO2, data shown in Fig. 4, there are several pronounced spikes in deep resistivity (near 2 m, 4.3 m, 5.5 m, and 15.8 m depths below surface) in sync with low points in medium and deep formation induction.

4.4 Microbiology

The microbiology of the serpentinite subsurface environment is being assessed through analyses of cores obtained during the drilling process and through on-going monitoring of fluids within the resulting wells. To assess microbial abundance within core materials, cells were extracted from formaldehyde-preserved samples, stained with the nucleic

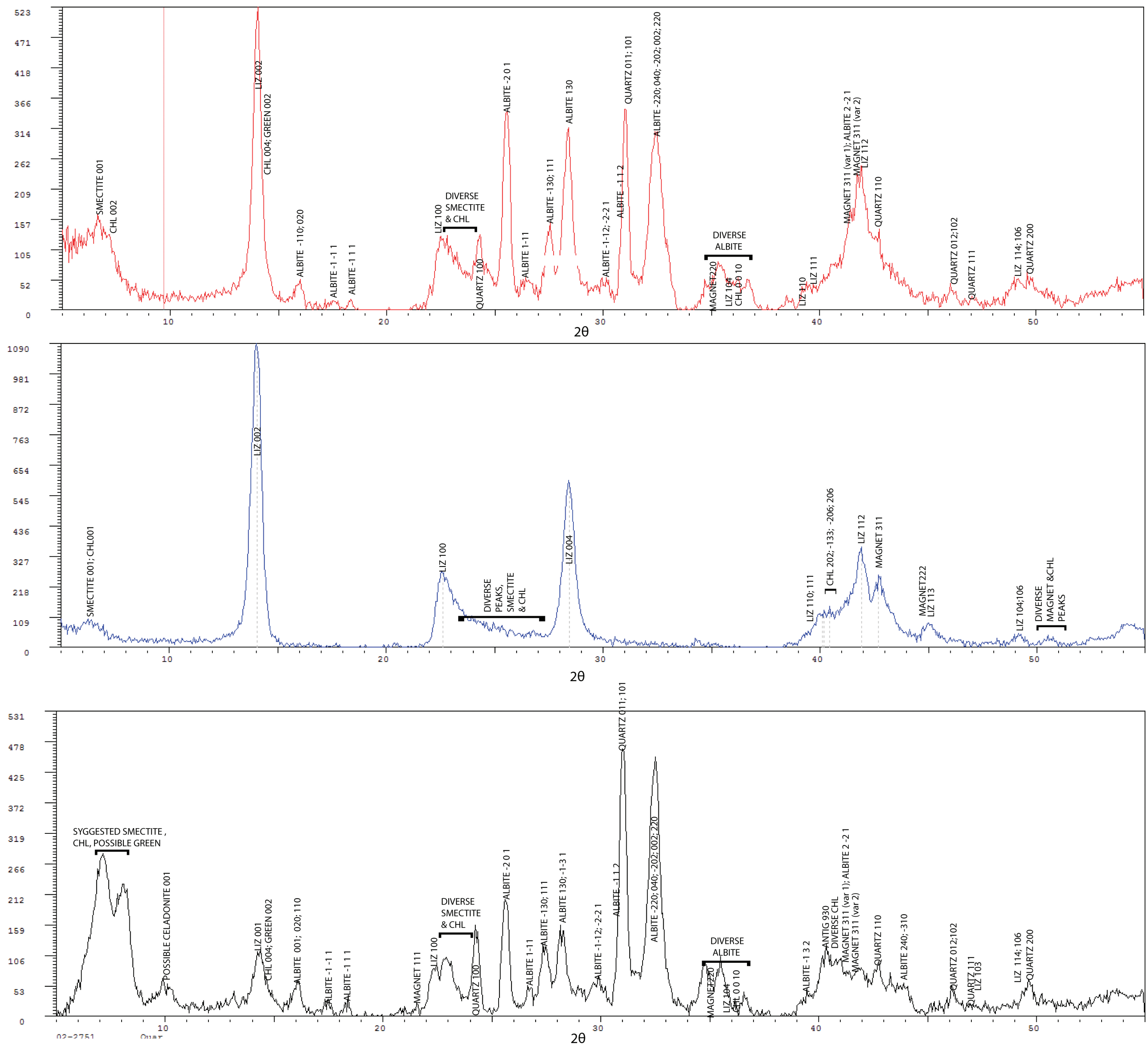

Figure 5. XRD profiles of representative samples from CROMO cores. Identified minerals are labeled, including smectite group clay minerals, chlorite (CHL), lizardite (LIZ), antigorite (ANTIG), greenalite (GREEN), albite, quartz, magnetite (MAGNET), celadonite. Note that lizardite, antigorite, and greenalite are all types of serpentine and not easily distinguished from each other based solely on XRD. Top: a shallow serpentine soil example; CROMO2, 3.5 m below surface. Middle: a magnetite-bearing serpentinite; CROMO2, 25.9 m below surface. Bottom: an example of a mixed core sample, with serpentine associated with products of basalt alteration in the subsurface; CROMO1, at 33.5 m below surface.

acid stain DAPI, and quantified microscopically. On average, between 10^5 and 10^7 cells per gram of rock material were evident through microscopic analyses. Fluorescent microbead tracers were quantified in the same preparations. Both culture-dependent and independent methods are being used to determine the microbial community composition of the cored materials. For culture-based approaches, solids from the cores were preserved under nitrogen headspace at 4 °C until being used as inoculum for culturing experiments in the laboratory. Enrichment media include incubations containing small organic acids, carbonate, and complex organic matter all under anaerobic or microaerophilic conditions. For culture-independent analyses, nucleic acids were extracted from flash frozen core using a MoBio Power Soil Kit (MoBio Labs, Carlsbad, CA). The resultant DNA was quantified using fluorometric methods, subjected to quantitative PCR of

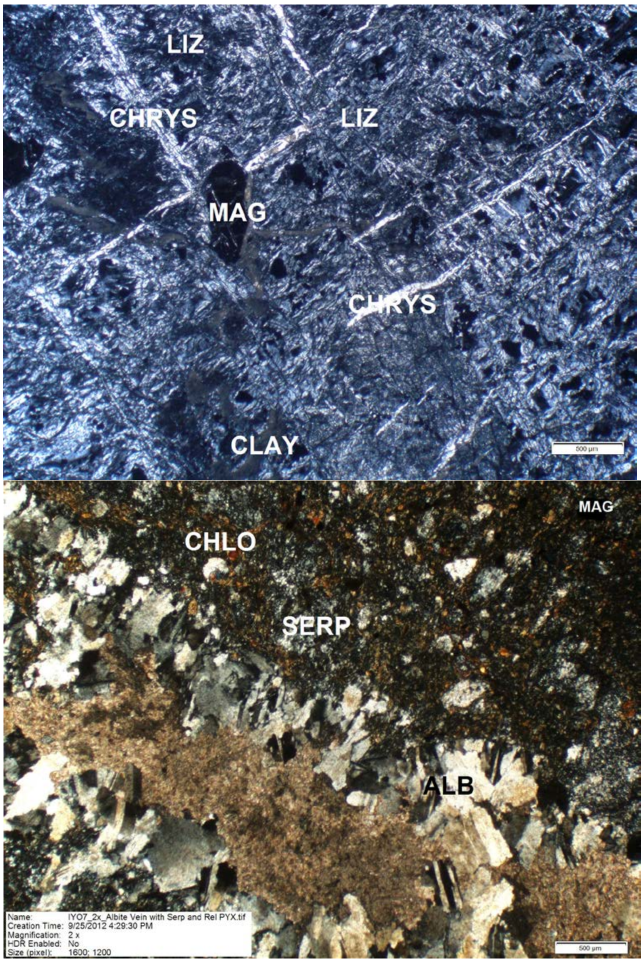

Figure 6. Representative thin sections. Top: CROMO2 at 41.15 m depth (2X). This thin section confirms the results from the XRD, showing lizardite as the dominant phase, the mesh-like white and blue matrix, with white veinlets of chrysotile and scattered black blebs of magnetite. Some clay minerals are present as well as opaque brown streaks. Bottom: CROMO1 at 31 m depth (2X). This thin section image was obtained with crossed polarizers applied. Albite crystals are the white and black twinned crystals that appear to extrude diagonally from the SE corner to the NW corner. Serpentine is present as black and white mottled mineral in the N and NE portion of the slide. Chlorite, another clay mineral shows up as slightly green-hued under cross-polarized light and is pervasive in the thin section.

the 16S rRNA gene of predominant taxa, and used to generate tag sequences. Preliminary results of cores samples suggest an exceptionally low diversity of microbes associated with solid substrates from the serpentinite subsurface environment.

Ongoing sampling of fluids from the wells includes DNA analyses of fluids concentrated via filtration and culturing of microbes using well fluids as inoculum. Initial results show evidence of phylotypes associated with heterotrophy, hydrogen oxidation, and sulfur and iron reduction in the biomass filtered from serpentinizing fluid samples.

4.5 Organic geochemistry

Initial efforts to extract organic compounds from the recovered cores have revealed low amounts of organic compounds. However, both bacterial and archaeal membrane lipids are present. Similarly, solvent extracts of borehole fluids from the adjacent Homestake monitoring wells have been found to contain only a few unusual organic compounds above detection levels, including thiolanes. Overall, initial results indicate that very limited amounts of organic matter may be present in the subsurface serpentinites.

5 Research implications

CROMO holds excellent promise as a platform for integrated biogeochemical probing of the serpentinizing subsurface. Core analyses show pervasively altered peridotite, and diverse secondary phases including serpentine, magnetite, carbonates, mixed clays. There is evidence for mafic rock alteration adjacent to ultramafic units, either by juxtaposition of ophiolite-derived mafic units or igneous sill emplacement. To date, findings include

- Bulk core mineralogy for both cored sites is dominated by lizardite (a serpentine polymorph), with magnetite, mixed clays, some albite (metamorphic alteration product), and actinolite/tremolite amphibole phases.
- Bulk core geochemistry shows intervals of elevated/peak iron, chromium, calcium, and titanium, which are likely mineral controlled.
- Field experiments with core materials and well fluids demonstrate biologically mediated uptake of added H_2 and CO, with fluids showing higher activity levels than core materials.
- Initial solvent extracts of subsurface rock samples indicate low levels and limited diversity of organic compounds, but include detectable amounts of membrane lipids from both bacteria and archaea.
- Preliminary DNA extractions have been successful and are being used to conduct metagenomics assays on CROMO samples. Microbial communities sampled are mostly dominated by bacteria, with variable occurrence of archaea. High relative abundances of Betaproteobacteria (which in general include hydrogen-oxidizers) have been observed in core samples from Quarry Valley, with closest relatives from other serpentinites in Portugal, the Cedars, and Lost City.

The main implication of these data is that serpentinization is ongoing, with high levels of hydroxide alkalinity and dissolved gases in the formation waters, and this is indeed an excellent hub for field investigations of this critical geobiological environment. Because this environment has been so little studied, the data constitute a new baseline for characterizing the habitability of serpentinizing systems. We anticipate rapidly growing interest in these boreholes, from colleagues in astrobiology and deep biosphere research areas, and from those involved in ocean drilling projects in similar earth materials. Management of the CROMO sites will be in accordance with the larger structure of research permitting and rules for the UC-Davis McLaughlin Natural Reserve.

The CROMO Scientific Party

The CROMO Scientific Party included D. Cardace, T. Hoehler, T. McCollom, M. Schrenk, D. Carnevale, M. Kubo, A. McCann, S. Som, I. Tiago, B. Brazelton, B. Nelson, and S. Chowdhury. K. Twing joined the project post-drilling.

Supplementary material related to this article is available online at http://www.sci-dril.net/16/45/2013/sd-16-45-2013-supplement.pdf.

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Scientific Drilling
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SCIMPI: a new borehole observatory

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Abstract. The Simple Cabled Instrument for Measuring Parameters in-situ (SCIMPI) is a new borehole observatory instrument designed to study dynamic processes below the seafloor. SCIMPI performs time series measurements of temperature, pressure and electrical resistivity at a series of depths, tailored for site-specific scientific objectives. SCIMPI's modular design enables tailoring of the type, depth distribution, and frequency of measurements based on the study goals and sediment characteristics. The first prototype is designed for 300 m below the seafloor in soft sediment and 1500 m b.s.l. However, SCIMPI could be tailored for deeper goals. The instrument can be configured for autonomous or cabled observatory deployments and has successfully undergone a number of tests, including pressure, communications, battery life, and interfacing with other drill-ship equipment. Here we discuss the design of the instrument, its capabilities, and the testing process it has passed through during four years of development. SCIMPI was successfully deployed on the Cascadia margin within the NEPTUNE Canada observatory network during IODP Expedition 341S in May 2013.

1 Introduction

A full understanding of earth system science requires the study of elemental (e.g., carbon and nitrogen) and heat fluxes across the seafloor–ocean boundary. Polar areas are currently responding the greatest to global warming and are of special interest for answering scientific questions about the processes of destabilization of permafrost and hydrates, which may accelerate the release of methane into the ocean and potentially the atmosphere. The amount of methane released from warming and its impact as a positive feedback in climate change remain undetermined. Methane reservoirs are also ubiquitous in other areas of the deep ocean in hydrate form and are an important, little-known component of the carbon cycle whose effect on global warming as greenhouse gases is a major component of this problem (Kvenvolden, 1995; Beerling et al., 2009).

SCIMPI (Fig. 1) is a borehole observatory instrument for placement in unconsolidated sediments. It will operate for two to four years on internal batteries that can be replenished via remotely operated vehicle (ROV) providing high spatio-temporal resolution measurements of the physical properties in the sediment, or connected to a cabled observatory system for real-time data acquisition. With either periodic battery replacement or connection to a cabled observatory, SCIMPI provides long-term observations for understanding sub-seafloor dynamics such as changes in seafloor and sub-seafloor gas hydrate systems. The main advantages of SCIMPI are its configurability, comparatively low equipment cost, and simple operational requirements, making it an economical and versatile system for scientific research.

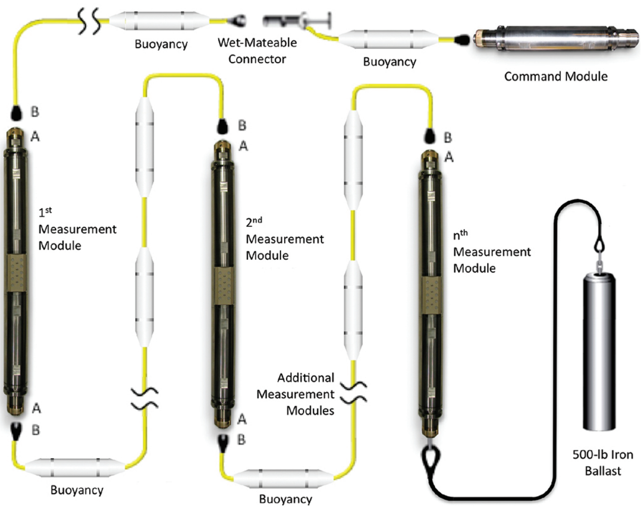

Figure 1. SCIMPI schematic showing the modules connected to each other to form a single string that was deployed in an open borehole to depths up to 300 m b.s.f.

2 System configuration and specifications

SCIMPI is designed for dynamic geotechnical conditions in which the borehole closes in on the device once the drill string through which it is emplaced is withdrawn. Borehole relaxation occurs because of two different processes: slower, creep-dominated deformation in fine-grained clays and shales, and immediate collapse in uncemented coarse-dominated sediments.

A SCIMPI string consists of multiple measurement modules and a command module connected by varying lengths of cable, with a ballast weight at the bottom of the string and flotation distributed along the string to keep the cable taut during deployment. It is powered and controlled via an underwater-mateable connection to either a ROV-replaceable command module or cabled observatory infrastructure. The modules and cable segments are physically daisy-chained while power and communications are on a multi-drop bus, a combination that provides several benefits. Each SCIMPI module is composed of interchangeable housing components that, with cables of varying length, allow any combination and distribution of sensors to be formed. Sensors currently included in SCIMPI modules are the Seabird Electronics SBE-38 precision oceanographic thermometer and the Paroscientific Digiquartz series 4000 pressure sensor, both commonly used in ocean sciences to characterize sub-seabed environments having dynamic fluid flow. Resistivity is measured by an Electrical Resistivity Smart Sensor (ERSS) from Transcend Engineering and Technology which acquires measurements from any Wenner-style (e.g., galvanically coupled, 4-electrode, Wenner, 1916) resistivity array. SCIMPI measurement modules each incorporate a Wenner-style array for measuring electrical resistivity of borehole sediments. The ERSS configuration can be tailored to the specific requirements of the deployment with the SCIMPI default set for a range of 0.1–100 Ωm using bi-polar excitation at 100 Hz. The ERSS does not correct internally for ambient temperature, as thermal effects are media dependent and should be considered in relation to the deployment medium during data analysis. All SCIMPI sensors are factory calibrated by their manufacturers. Additional 5 to 15 VDC sensors that communicate via RS-485 can be added without requiring software or circuit modifications.

Other benefits of the design are efficient power management and flexible communications. Each measurement module contains a Texas Instruments MSP430-based processor responsible for powering and communicating with up to four sensors on an internal two-wire RS-485 bus (Fig. 2). Each sensor's power is isolated and individually switchable. A low voltage signal from the command module activates all measurement modules when needed, causing them to latch on to the external power bus, boot up, and await instructions.

Inactive measurement modules consume a few microwatts of power. Active modules respond to a Modbus RTU-compliant protocol over an external two-wire RS-485 bus that connects all modules. The protocol encapsulates each sensor's command set, so software revisions are not necessary to support new sensors. Power is supplied to all modules via a two-wire bus that allows battery packs to be distributed anywhere in the SCIMPI system string. Internal battery packs deliver 16 500 mAh at 14 V using primary lithium-thionyl chloride cells. Distributing the battery power throughout the modules limits the required module size to allow a complete autonomous SCIMPI to be deployed through the drill pipe without needing an ROV. Back-charging is prevented so that power initially provided by modules down in the borehole can be replaced by power from a module containing fresh batteries at the seafloor.

The command module, which remains above the seafloor, contains power conversion and seawater isolation circuitry, a programmable datalogger, and can be extended to hold additional battery packs. The datalogger is a single-board computer (SBC) based on an ARM9 processor running Microsoft's dot-NET Micro Framework. To conserve power, the SBC is supervised by a TI MSP-430 microcontroller that includes a real-time clock, keeps track of the datalogger's status, and powers up the dot-NET system to acquire data according to the user-defined schedule. The system records data to log files in ASCII format with UTC time stamps on a 32-GB SD memory card.

SCIMPI is configured via a Windows application, "SCIMPI Config", provided by Transcend Engineering and Technology. The program enables the user to specify sensor commands, sequences of sensor power switching and polling, and the overall polling interval. The command module automatically switches between different operational modes depending on the status of its "up-hole" and "down-hole" ends. *Cabled* mode is automatically entered whenever

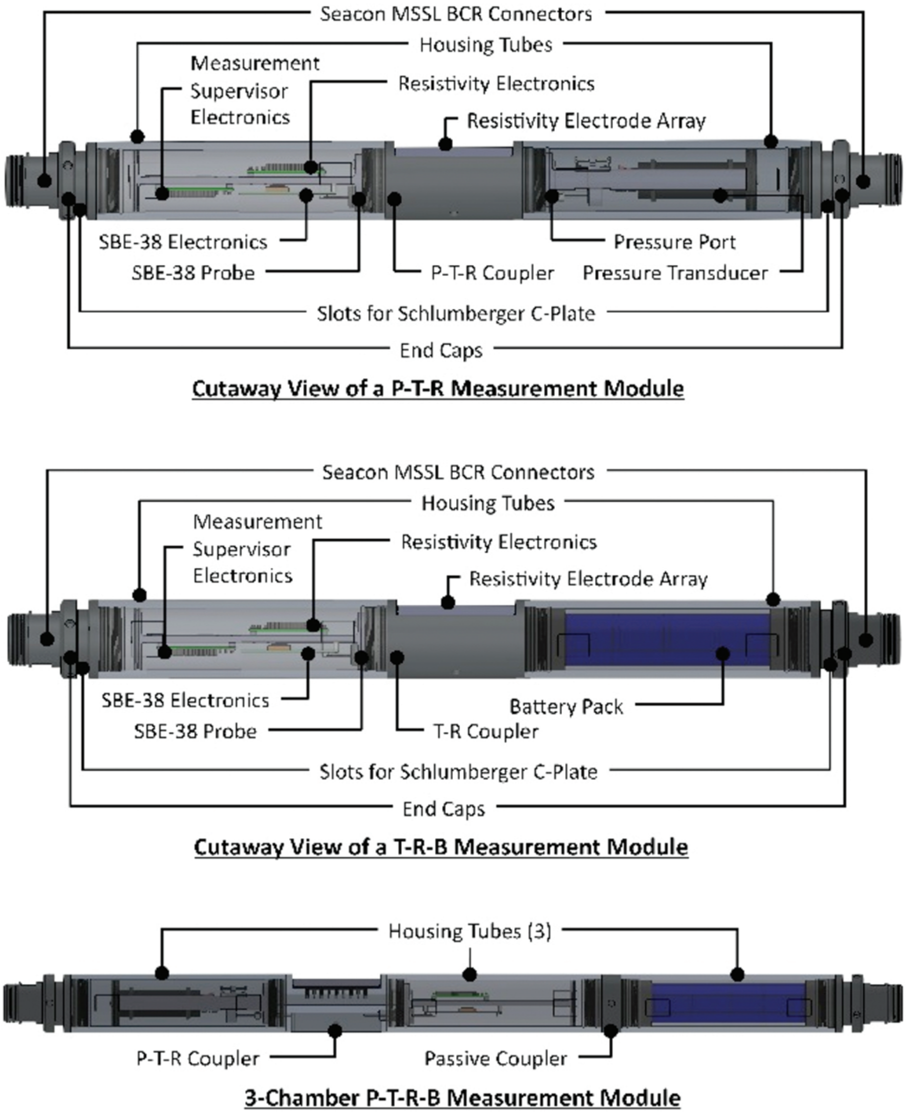

Figure 2. Cutaway view of: PTR (pressure-temperature-resistivity) measurement module (above), TRB (temperature-resistivity-batteries) measurement module (center) and PTRB (pressure-temperature-resistivity-batteries) measurement module (below).

power (9 to 80 VDC) is applied to the up-hole end, such as through a wireline umbilical or cabled network. In *cabled* mode, SCIMPI acquires measurements continually and writes time-stamped ASCII data to the up-hole RS-485 bus in addition to the internal SD memory card. When up-hole power is removed, SCIMPI enters *autonomous* mode. In this mode, the command module electrically isolates the up-hole connector to avoid any connection with seawater, and enters an ultra-low-power sleep mode that is interrupted at a user-specified interval to acquire and record measurements. SCIMPI will be lowered into its borehole in *cabled* mode while powered via the drill-ship's wireline cable. Upon release, it will automatically switch to *autonomous* mode powered by the internal batteries. If connected via ROV to cabled observatory power, SCIMPI will again enter *cabled* mode and produce data continually.

SCIMPI is designed for a water depth of 6000 m b.s.l. and a sediment depth up to ~1200 m b.s.l. Although the first SCIMPI prototype is limited by its flotation material to 1500 m b.s.l., the flotation of the system can be adapted to different site depths. The flotation keeps the SCIMPI cable taut during installation with the underwater-mateable connector and command module accessible above the seafloor during installation. In a similar way, the depth below seafloor of the first prototype is 300 m, but future systems could go as deep as 1200 m (maximum depth below seafloor based on the RS-482 communication protocol).

Table 1. Specifications of the SCIMPI prototype.

Temperature (Modified Seabird SBE-38)	Electrical Resistivity Smart Sensor (ERSS)	Pressure (Paroscientific Model 410K-101)	Housing (Standard Measurement Module)
Range: −5 to +35 °C Resolution: 0.00025 °C	Range: 0.1 to 100 Ωm (default reconfigurable)	Range: 0 to 10 000 psi (other ranges available)	Diameter: 76.2 mm Length: 870 mm Weight: 16.4 kg
Absolute accuracy: ±0.001 °C Deployment accuracy (3 yr): ±0.007 °C	Absolute accuracy: 0.025 Ωm	Absolute accuracy: 0.01 %	Material: 17-4PH Stainless Steel, condition H1025
Drift: ±0.001 °C per 6 months	Resolution: 0.00001 Ωm (reconfigurable)	Resolution: 0.0001 %	Design pressure: 8760 psi

The first SCIMPI prototype is equipped to measure temperature, electrical resistivity, and pressure (Table 1). The design allows other sensors to be easily added, and we expect to incorporate other types of measurements in the future.

3 Testing and deployment

All SCIMPI housings were designed and pressure tested to 60 MPa and all sensors are factory calibrated by their manufacturers and inspection tested prior to integration. The integrated system was tested both on land and at sea, with final pre-deployment testing completed in November 2011. SCIMPI was successfully deployed in the Integrated Ocean Drilling Program Site U1416 in May 2013, Expedition 341S. The R/V *Thompson* revisited this location on 24 June 2013 (Fig. 3). SCIMPI was specifically designed to be deployed through the drill pipe of the D/V *JOIDES Resolution* so no re-entry cone or casing is required. The borehole needs to be drilled to the target depth using a bit with a diameter of 9–7/8′′. The bit is dropped and SCIMPI is lowered down the drill string, suspending it when needed in the Schlumberger C-plate as it is fed into the drill pipe. During deployment, the multi-function telemetry module (MFTM) designed by Lamont Doherty Earth Observatory Borehole Research Group enables continuous serial communication with SCIMPI through the Schlumberger wireline cable. Once lowered to target depth in the borehole, SCIMPI is released using the electrical release system (ERS) designed and built by Stress Engineering, the wireline cable, ERS, and MFTM are retrieved, and the drill pipe is tripped out over the SCIMPI, leaving the observatory in place.

When deployed as an autonomous instrument, SCIMPI requires servicing by an ROV every two to four years to swap out the command module. If SCIMPI is connected to a network for electrical power and real-time data reporting, then an ROV is required only to complete the initial connection.

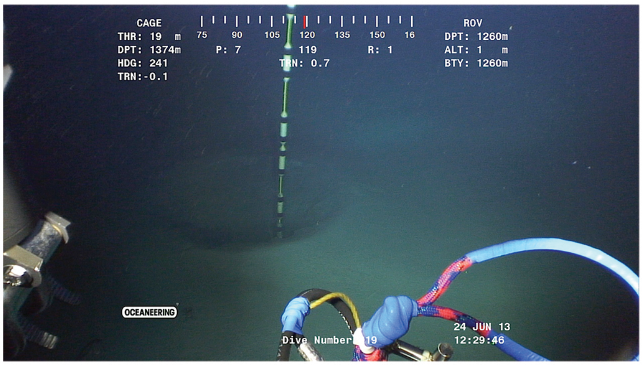

Figure 3. SCIMPI installation in the seafloor at Site U1416 as imaged with an ROV on 24 June 2013, Oceans Network Canada dive No. 19 to the Clayoquot Slope region (Image ©: Ocean Networks Canada).

4 Flexibility in the configuration

The adjustable spacing between SCIMPI modules is one of the major advantages of the instrument. This spacing can be flexibly adjusted during a drilling expedition using core recovery and log data from the deployment site to determine optimal module positioning. To ensure this flexibility, spare cables with varying lengths will be carried on board allowing the science team to configure the instrument based on sub-seafloor characteristics determined from the interpretation of the first holes drilled. Lado-Insua et al. (2012) has developed a methodology to calculate the number and optimal distribution of modules so that long-term data from SCIMPI captures the sediment intervals with most potential for determining dynamic fluid flow processes.

For example, the formation of gas hydrates requires particular conditions of pressure and temperature. SCIMPI's sensors make it ideal for the study of gas hydrate dynamics. The stability of gas hydrates is generally assessed based on geothermal gradients (Gorman and Senger, 2010). These models could be better determined by using several SCIMPI installations in an area. Spatial and temporal gradients in pressure and temperature can be determined to study lateral changes in the geothermal setting. The use of SCIMPI in these environments can provide unique information on gas hydrate changes in electrical resistivity and overpressure due, for example, to processes related to changes in pore pressures. We expect SCIMPI to provide insight into the dynamics of gas hydrates in areas affected by climate change (e.g., in the Arctic where warming is amplified), fluid flow (e.g., subduction zones), and methane release (e.g., outer continental shelves and slopes).

5 Summary

SCIMPI is a new seafloor observatory in its final stages of development. A prototype has undergone thorough testing and was successfully deployed in May 2013. SCIMPI can measure long-term time series of temperature, pressure and electrical resistivity spatially at multiple depths below the seafloor. The instrument is highly modular and customizable to different environments, different spatial distributions of sensors, and autonomous as well as cabled operation. SCIMPI is designed for deployment into soft sediments directly through the drill string to minimize equipment and operational costs and can operate autonomously for several years on battery power.

Science applications of SCIMPI include studies of fluid flow, hydrate formation, and seismically induced pore pressure changes. The Arctic Ocean is an area particularly suited for SCIMPI deployment. Kitidis et al. (2010) demonstrated the existence of water and sediment sources of methane and nitrous oxide in the Arctic Ocean, that indicate that future sea-ice retreat may increase the flux of these gases from the sea to the atmosphere. They pointed out the importance of spatio-temporal studies of these systems. Long term time series of their variations obtainable using SCIMPI may prove critical to understanding their dynamics.

SCIMPI's comparatively low cost will enable time series measurements to become more commonplace, thereby improving our temporal and spatial knowledge of sub-seafloor gas, fluid, and pore pressure activity. Most notable among potential deployment targets for SCIMPI are sites with sub-seafloor gas hydrate and those with biogenic methane. Understanding the dynamics of methane's role in the oceans as climate change proceeds will contribute to a better understanding of the earth's carbon budget.

Highlights

- SCIMPI is a new borehole observatory designed to record physical properties time series.
- The first prototype is able to measure temperature, electrical resistivity and pressure.
- SCIMPI can run on batteries that require refreshment after two years, or it can be powered from a cabled network to provide real-time measurements.
- SCIMPI is ideal for studies of dynamic environments such as gas hydrates

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Scientific Drilling
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Scientific drilling and the evolution of the earth system: climate, biota, biogeochemistry and extreme systems

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Abstract. A US National Science Foundation-funded workshop occurred 17–19 May 2013 at the University of Oklahoma to stimulate research using continental scientific drilling to explore earth's sedimentary, paleobiological and biogeochemical record. Participants submitted 3-page "pre-proposals" to highlight projects that envisioned using drill-core studies to address scientific issues in paleobiology, paleoclimatology, stratigraphy and biogeochemistry, and to identify locations where key questions can best be addressed. The workshop was also intended to encourage US scientists to take advantage of the exceptional capacity of unweathered, continuous core records to answer important questions in the history of earth's sedimentary, biogeochemical and paleobiologic systems. Introductory talks on drilling and coring methods, plus best practices in core handling and curation, opened the workshop to enable all to understand the opportunities and challenges presented by scientific drilling. Participants worked in thematic breakout sessions to consider questions to be addressed using drill cores related to glacial–interglacial and icehouse–greenhouse transitions, records of evolutionary events and extinctions, records of major biogeochemical events in the oceans, reorganization of earth's atmosphere, *Lagerstätte* and exceptional fossil biota, records of vegetation–landscape change, and special sampling requirements, contamination, and coring tool concerns for paleobiology, geochemistry, geochronology, and stratigraphy–sedimentology studies. Closing discussions at the workshop focused on the role drilling can play in studying overarching science questions about the evolution of the earth system. The key theme, holding the most impact in terms of societal relevance, is understanding how climate transitions have driven biotic change, and the role of pristine, stratigraphically continuous cores in advancing our understanding of this linkage. Scientific drilling, and particularly drilling applied to continental targets, provides unique opportunities to obtain continuous and unaltered material for increasingly sophisticated analyses, tapping the entire geologic record (extending through the Archean), and probing the full dynamic range of climate change and its impact on biotic history.

1 Scientific rationale

Over the past decade, numerous workshops and study groups within sedimentary geology, paleoclimatology, and paleobiology have repeatedly highlighted the importance of continental scientific drilling to address important science questions in climate and linked earth systems (e.g., the US National Science Foundation (NSF)-supported GeoSystems, DETELON, and Transitions workshops, and the US National Research Council (NRC) reports on Deep-Time Climate and Climate and Human Evolution, Soreghan et al., 2003, 2005; Montanez and Soreghan, 2006; Bottjer and Erwin, 2010; NRC, 2010, 2011; Parrish, 2012). In recognition of this sustained surge of interest, a workshop was held on 17–19 May 2013 at the University of Oklahoma to identify high-priority targets for scientific drilling aimed at assessing critical questions related to paleoclimate, paleobiology, and extreme events in earth's history. The objectives of the workshop were to (1) develop a community of researchers interested in using scientific drilling for stratigraphic targets to answer questions about earth system evolution, (2) identify topics and drilling targets of broad scientific interest, and

(3) offer researchers direction on how to develop compelling drilling proposals, how to evaluate and plan logistical issues related to drilling, and how to develop a funding plan for drilling strategically. The ultimate intent is to galvanize research teams to move forward with future proposals involving continental drilling.

2 Workshop format and proceedings

All interested researchers were invited to submit a brief pre-proposal identifying a viable continental scientific drilling target to examine questions of scientific importance in the areas of paleoclimate, earth history, stratigraphy, paleoecology and/or paleobiology from any interval of earth history. The 41 participants submitted 30 pre-proposals that articulated scientific themes in earth, and evolutionary and ecological history spanning geologic time. Participants discussed the role of drill core studies in earth/life history and identified locations where critical questions can best be approached.

The workshop included plenary sessions in which invited speakers addressed topics of overarching interest in scientific drilling. Additionally, principal investigators for each submitted pre-proposal presented a 5 min talk outlining the science drivers, significance, and rationale to enable all participants to grasp the vast breadth of proposed projects, which span the geological record from the oldest sedimentary rocks to modern lakes, and range geographically from pole to pole (Fig. 1 and Appendix Table A1).

Through the rest of the 2.5-day workshop, breakout groups identified critical science questions in earth history that can be assessed with drill core data, and evaluated discipline-specific drilling problems. Themes were chosen to explore earth history processes across timescales, and to consider how drilling can inform our understanding of those events.

3 Glacial–interglacial and icehouse–greenhouse transitions and biotic consequences

Earth's atmosphere reached a historic threshold in May 2013, when sustained atmospheric CO_2 levels exceeded 400 ppmv for the first time in human history, and the first time in approximately 3 My (Beerling and Royer, 2011). Passing this threshold offers the opportunity to engage the public in climate transitions in earth history, and the earth system linkages accompanying these transitions, such as changes in biodiversity and ecosystems during glacial–interglacial transitions. To this end, much research has focused on, in particular, the transition from the Last Glacial Maximum (LGM) to our current interglacial, as well as other transitions within the Pleistocene (e.g., Fawcett et al., 2011; Ivory et al., 2011; Brigham-Grette et al., 2013). These studies provide important insights into earth's climate behavior at a very high-resolution (millennial to annual) scale that are critical for grasping earth's recent climate behavior and informing deep-time studies of glacial–interglacial transitions. It is equally important, however, to understand the potential diversity of glacial–interglacial behavior throughout earth's record. What insights can we gain into climate behavior by examining Paleozoic and Neoproterozoic glacial–interglacial and – at a broader scale – so-called "icehouse–greenhouse" transitions (e.g., Bao et al., 2008; Fike et al., 2006; Kennedy et al., 2008; Mills et al., 2011; Barham et al., 2012)? Research over the past decade has highlighted the occurrence of major biological turnovers in earth history accompanied by changes in greenhouse forcing, ocean acidification and climate change (e.g., Jiang et al., 2009; Johnston et al., 2012; Katz et al., 2008). Continental drilling can provide high-resolution records of these climate and life transitions. Looking back into the period of the Cenozoic when atmospheric CO_2 levels differed from today provides estimates of future climate change and ecological response. The deep past also highlights abrupt change, the information necessary to test how well climate models will predict abrupt changes in the coming centuries (Valdes, 2011). The Paleozoic and Neoproterozoic icehouse–greenhouse transitions provide particularly extreme examples that, albeit poorly constrained, span evolutionary events such as the origin of animals and terrestrial ecosystems central to our existence.

4 Records of long-term evolution events and extinctions

Developing reliable records of evolution and extinction requires access to high-resolution geochronological control, and also unambiguous superposition, which is a great benefit of drill core over purely outcrop studies. Furthermore, both micro- and macrofossil records are critical for assessments of life transitions, so linked outcrop and coring studies are critical for questions targeting these issues. In addition, a core provides access to unweathered material critical for geochemical analyses, including organic (e.g., biomarker) and potentially fossil DNA studies, which can shed light on ecological (including catastrophic) events and evolutionary history (e.g., Clyde et al., 2013). Effective strategies for obtaining sufficient sampling across critical intervals include planning for multiple shallow cores across a series of dipping strata, or targeted coring of key intervals defined by nearby outcrop studies. Drill cores eliminate the human bias of outcrop-based studies by taking an essentially random sample of local sedimentary facies through time and providing a continuous (albeit not necessarily complete) stratigraphic record across biotic transitions.

5 Records of major biogeochemical events in the oceans

The first oxygenation of the atmosphere and ocean is a critical biogeochemical event in earth history. This transition

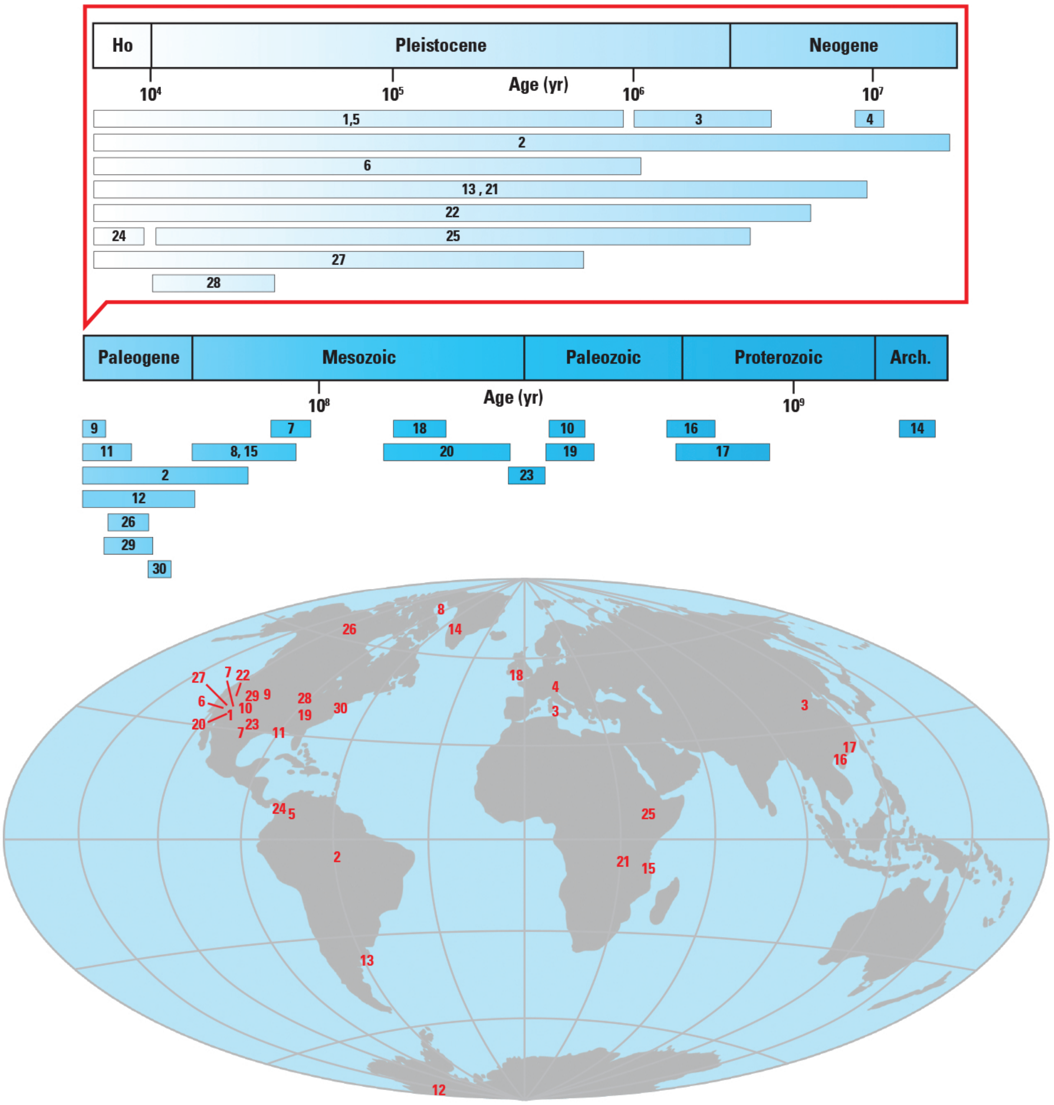

Figure 1. Geologic timescale (above) and global map (below) listing the (enumerated) 30 drilling project pre-proposals submitted to this workshop. The gray to black bars show the various timescales of the projects proposed. Note that the upper timescale is an enlarged version of the Holocene through Neogene interval, to portray projects proposed for this "near-time" slice. See Appendix Table A1 for the titles of the proposed projects (key to the numbers in the bars in this figure).

was a prerequisite to the appearance of eukaryotic organisms and ultimately to emergence of animals and their major radiation – the Cambrian explosion. Many evolution and extinction events, especially those in earth's Precambrian record, are tied either directly or indirectly to oxygen availability. Research on Precambrian earth systems has experienced a resurgence of interest as new geochemical tools have come online to assess these events – especially various redox-sensitive metal tracers and their isotope systematics (Buick, 2007; Scott et al., 2008; Partin et al., 2013; Reinhard et al., 2013) and basin-scale reconstructions of redox state (Sperling et al., 2013a, b) that enable tracking of oceanic oxygen levels.

Collectively, this work demonstrates that the view of a single large oxygenation event yields to a model of dynamic rises and falls in oxygen levels. This requires that the precision of our proxies increase and/or expand to meet the constraints placed by physiology (microbial and metazoan) in order to understand earth's major biological transitions (Sperling et al., 2013). Improved understanding of Precambrian oxygenation events also informs views of the global ocean redox landscape during Phanerozoic anoxic events (Lyons et al., 2009). Drill-core records provide a unique and fundamental opportunity to assess timing, duration, and possible drivers of these events, owing to their capacity to provide both continuous and, critically, unweathered (unoxidized) material. Beyond the ocean, coring of paleosols sheds light on the spread of oxygenation to continental systems and a direct measure of atmospheric oxygen. Further, refined data on ancient oxygen conditions inform our view of ocean deoxygenation scenarios under recent human influences, such as lower oxygen solubility in warmer surface waters and elevated riverine nutrient delivery (e.g., Falkowski et al., 2011).

Although atmospheric and oceanic oxygenation are tied directly or indirectly to many of the most fundamental biogeochemical events in earth history, other events best accessible through continuous and unweathered cores include ocean-acidification events (e.g., the Permian–Triassic and Paleocene–Eocene Thermal Maximum, as potential analogs for earth's near-term future, e.g., Zachos et al., 2005), the C_3–C_4 vegetation transition, and the effect on global carbon cycling linked to the radiation of diatoms and calcareous nannoplankton more recently (Katz et al., 2005). Drill cores can also provide links between oceanic and continental records to assess the role of continental processes such as nutrient recycling during times of oceanic anoxia, for example, and to evaluate the "buffering" capacity of the oceans at times of high $p\mathrm{CO}_2$.

6 Core records of reorganization of earth's atmosphere

Earth's atmosphere has evolved and reorganized through time as reflected by changes in (1) chemical composition, such as the presence and proportions of O_2, CO_2, and SO_2, (e.g., Kump, 2008; (2) aerosol composition, including the presence and proportions of mineral dust and black carbon, and – speculatively – dimethylsulfide and O_3 (Wolff et al., 2010; Diessel, 2010; Bisiaux et al., 2012); and (3) circulation, such as the position of the Intertropical Convergence Zone (ITCZ), presence and strength of monsoons, and storm intensity (e.g., Ito et al., 2001; Frappier et al., 2007). Key events in atmospheric reorganization include both Precambrian and Phanerozoic shifts in (1) O_2 in response to evolutionary radiations of photosynthesizers (Canfield et al., 2007); (2) CO_2 in response to biological, tectonic, and weathering drivers (Bergman et al., 2004; Berner, 2006); and (3) atmospheric circulation (e.g., shifts from zonal to monsoonal circulations associated with continental positions and mountain elevations) (e.g., Parrish, 1993; Clift et al., 2008). Proxies and indicators useful to reconstructing atmospheric composition include various approaches to measuring, for example, atmospheric CO_2 such as paleosol carbonate isotopes, leaf stomatal densities, and bryophyte photosynthetic fractionation (e.g., Royer et al., 2001; Fletcher et al., 2008). Proxies and indicators exist for temperature, moisture, and transport, such as various isotopes, biomarkers, and eolian provenance indicators (e.g., Soreghan et al., 2002; Eglinton and Eglinton, 2008; Severman and Anbar, 2009; Pullen et al., 2011; Woltering et al., 2011; Zambito IV and Benison, 2013), all of which benefit from pristine material offered by drill cores. Target records include loess deposits, paleosols, lacustrine and epeiric marine strata, and facies conducive to preservation of leaf waxes and associated biomarkers (e.g., Brigham-Grette et al., 2013). Drilling of continental records is particularly needed to assess the range of responses on the continents to global change. The integration of proxy results to constrain climate models offers the potential to refine predictions for future sea level and agricultural productivity under higher levels of greenhouse gases.

7 *Lagerstätte* and exceptional fossil biota in cores

Some continental cores preserve fossil *Lagerstätten* (exceptionally preserved fossil biota) of microfossils or very small macrofossils (Pearson et al., 2006; Wendler et al., 2011; Wolfe et al., 2006). Microfossil *Lagerstätten* in cores are especially useful for yielding estimates of true diversity (Jiménez Berrocoso et al., 2010). Cores can also provide critical sedimentary and geochemical context for *Lagerstätten* of larger fossils or extraordinarily preserved sedimentary deposits (e.g., varves or tidalites) that give detailed records of environmental conditions. Access to such deposits via core recovery facilitates high-resolution geochronological correlation and provides well-preserved samples with no weathering overprint. Analyses of *Lagerstätten* in the context of continuous core can reveal biotic sensitivities to environmental change and shed light on kill mechanisms during extinction events. As such, cores containing fossil *Lagerstätten* or exceptional sedimentary deposits offer key insights on the evolution of earth's system states over time.

8 Drill core records of vegetation and landscape change through time

Landscapes reflect the combined effects of physical, biological, and (since humans evolved) anthropogenic influences occurring on earth's surface over time, and thus preserve a 4-D record of processes affecting a sedimentary basin (Driese and Nordt, 2013). Vegetation and landscape changes are identified through composition of and changes in, for example, fossil flora (e.g., leaves, wood, seeds, flowers, root traces, phytoliths, palynomorphs, charcoal, etc.), trace fossils, paleosols, thermochronological signatures, and various isotopic records. The geologic record of landscapes is best addressed by an approach that combines outcrop studies (where feasible) with drilling – the former to access records such as megaflora, and the latter to enable geochemical analyses of pristine material (e.g., Retallack and Dilcher, 2011).

Outstanding issues in landscape analysis that could benefit from systematic inclusion of drill core records include (1) linking sediment sources to sinks, (2) characterizing extinct soil types and ecosystems, (3) determining spatial variability in fossil landscapes, and (4) determining uplift histories (potentially rates and reliefs and even paleoelevation through time now accessible by detrital thermochronology). Ultimately, core analyses could enable systematic analysis of the evolution of earth's critical zone through time. With regard to landscape analysis, even the surfaces encountered in cores – the hiatal events – provide key data for landscape reconstruction (e.g., Nordt et al., 2013; Sauer et al., 2013). Beyond the deep-time geological record of landscape change, the recent anthropogenic record offers insights into landscape changes wrought by pre-industrial human transformations, especially the commonly recognized but poorly characterized history of anthropogenic deforestation and fire use (Ruddiman, 2013). Cores may allow us to distinguish the onset timing and magnitude of human-induced fire, for example in the fire-adapted ecosystems of the African miombo or Australian woodlands.

9 Paleobiology

Recovery of adequate macrofossil assemblages and fragile or flat biota in cores is possible, and could be maximized in novel ways not available to paleobiologists relying on a single core. For example, multiple cores taken along a transect, or through recovery of long lateral sections via horizontal drilling of fossiliferous units, and inclusion of outcrop studies can best account for assemblage characteristics. The usefulness of paleobiologic records, especially if biogeochemical analyses are envisioned, can be compromised by potential contamination, so logistical issues are critical, including choice of lubricants, drilling fluids, and core recovery techniques (e.g., use of liners, etc.), as well as post-drilling core handling and curation (cutting, sieving). A processing technique should be planned so as to avoid inadvertent destruction of macro-remains. Use of analytical methods such as X-rays and CT scans can be extremely helpful for imaging macrofossils as well as traces in 3-D and in situ, to reveal the occurrence of thin or small specimens that might be enigmatic in 2-D slab cuts. Much as yet unexplored potential exists in the integration of paleobiology with genomics/molecular genetics/protenomics in unweathered drill core samples (Cohen, 2011).

10 Stratigraphy/sedimentology

All stratigraphic/sedimentary studies benefit from recovery of pristine, continuous records, uniquely offered by drilling. In addition, a core provides critical tie points that link outcrop with seismic imaging data sets. This is essential for building robust, basin-wide chronostratigraphic frameworks that ensure reproducible correlations. The spatial perspective, coupled with linkages to paleoecological research in complex terrestrial environments, suggests that multiple drill cores or core transects may be required to address interdisciplinary research objectives in some basins. Key subject areas for science questions that can be addressed in the realm of stratigraphy and sedimentology include large-scale basin geodynamics and source-to-sink issues (e.g., sediment budgets, long-term erosion rates, subsidence analysis, fault evolution), including biogeomorphological feedbacks, such as source–sink systems at major earth/life and climatic transitions. For example, fluvial records show a fundamental shift in stratigraphic architecture associated with major phytogeographic changes (Ward et al., 2000; Davies and Gibling, 2009) – an important set of transitions in the Phanerozoic earth system (atmosphere–biosphere). At finer timescales, cyclostratigraphy applied to continental drill core holds promise for casting new light on the dynamics of earth's orbit (e.g., Olsen and Kent, 1999). Cyclostratigraphic insights span timescales beyond the well-known application to Milankovitch periodicities, including diurnal records that reveal profound changes in earth's speed of revolution and interactions among the Earth–Sun–Moon system. Drill core stratigraphic records likewise hold strong potential for preserving sedimentary evidence of catastrophic "events" important to the evolution of the earth system, including ancient storms, earthquakes, and volcanoes. Drill core studies applied to such issues can be greatly augmented through the collection of ancillary geophysical logs for color spectra, neutron, formation imaging and geochemical element logging.

11 Geochemistry/geochronology

Best practices for maximizing recovery of geochemical and geochronological information from drill cores include (1) obtaining core orientation for paleomagnetic and fabric studies, (2) minimizing variation in core description by involving a minimal number of observers, (3) routine XRF and UV scanning (highlighting occurrences of, for example, tephras), and measurement of downhole temperatures (which can shed light on incipient diagenesis, and augment auxiliary databases relating to, for example, trends in climate warming and heat flow).

The importance of special handling to maximize recovery of geochemical and geochronological data merits creation of a study committee to create a best-practices document to detail contingency preparation (long-term core sample storage for analyses using future technologies), and how to strategize recovery of information with cost-effectiveness. From the initial drilling to core handling and curation, care should be taken to record all "metadata" associated with core capture and subsequent treatment – any action that could potentially impact future analyses, such as (1) characterization of all drill site fluids and lubricants used, (2) sampling of pore fluids, and (3) subsequent storage conditions of the core (e.g., dry at ambient temperature, dry at 4 °C, frozen, or stored in an N_2 (anoxic) atmosphere). Such "best practices" are applicable to many data sets beyond geochemistry and geochronology.

Potential geochronological approaches useful for sedimentary core material include U–Pb (tephras, detrital zircons), Ar–Ar (feldspars from tephra), Re–Os (organic-rich shales), Lu–Hf (phosphorites), Pb–Pb (carbonates, primary and secondary), and Sr isotopes. Other useful methods include low to moderate temperature thermochronology using U–Th–He, and Ar–Ar, and thermochronology/geochronology (e.g., C-14, U-series disequilibrium, thermo-luminescence, cosmogenic nuclides, etc.). Exciting novel geochemical proxies include redox metal and isotopic approaches to assess productivity, methods to assess paleo-redox conditions, temperature, pH and $p\mathrm{CO}_2$, weathering and hydrothermal fluxes (e.g., Anbar and Rouxel, 2007; Severmann and Anbar, 2009; Frank, 2011; Pufahl and Hiatt, 2012). Many of these techniques depend on the acquisition of pristine materials best obtained from core samples.

12 Science drivers

Closing discussions at the workshop focused on the overarching science drivers for which drill core can make a difference in our understanding of the evolution of the earth system. The key theme, holding the most impact in terms of societal relevance, is that of climate change and biotic evolution. More specifically, how do transitions in climate drive biotic change, and what role can unweathered, stratigraphically continuous scientific drill cores play in advancing our understanding of this linkage, and the relevant processes (e.g., Jaramillo et al., 2010)? In the face of growing concerns over the current pace and possible future impacts of climate change, we must understand how climate changes archived in earth's past have affected life (i.e., to assess the biotic tolerances of environmental changes) at all timescales. This is best done by focusing on times in the geologic past that capture transitions in climate states (e.g., Parrish et al., 2012). Tied to this theme, albeit at longer timescales, is research on climatic–tectonic feedbacks, to understand the full range of how climate has varied on earth.

Other areas that could be addressed by drilling include research on the function and history of the "geodynamo", and long-term solar-system dynamics – topics that arose from consideration of the centrality of geochronology to all other endeavors relating to scientific drilling of stratigraphic targets. Pursuit of these areas could ultimately lead to a fully calibrated astrochronology through the Paleozoic.

13 The unique role for continental drilling

Scientific drilling, and particularly drilling applied to continental targets, provides truly unique opportunities in earth science research. Perhaps the key opportunities are the abilities to (1) obtain pristine material suitable for geochemical and (potentially) paleogenomic analyses; (2) obtain a continuous stratigraphic record with minimal sampling gaps, especially in depocenters poorly exposed in outcrops; (3) tap earth's entire geologic record (extending through the Archean); and (4) tap the full depth of the dynamic range of climate change (see below).

Outcrop-based studies are and will continue to be fundamental for research on earth-system evolution. However, as our abilities to extract climatic and biotic data from the past have grown, most notably from an abundance of novel geochemical approaches, the need for pristine sedimentary samples has become paramount. Indeed, the very "shelf life" of cores may be more limited than previously recognized, owing to the emergence and growth of analyses utilizing organic biomarkers, redox-sensitive transition metals, and DNA analyses, all of which rely on availability of fresh, unoxidized material. The potential utility of core for such analyses becomes compromised the moment the core is exposed to the atmosphere. Addressing this issue, and especially the possibility of archiving material for use in perpetuity, may require future workshops on novel approaches to core archival. These could include the storage of sample splits in anoxic conditions. In addition to providing pristine sample material, drill cores have long been recognized as the primary means to obtain a continuously sampled section, and – where the drilling site is chosen to maximize it – to obtain a stratigraphically continuous section. The latter is particularly critical in the case of basin depocenters in tectonically stable regions lacking outcrop. The value of such archives only increases as new tools for continuous core analysis become routine, including, e.g., whole-core CT scans, XRF scans, etc.

The rich potential offered by drilling the continental record remains vastly underutilized. Ocean drilling has provided paradigm-shifting insights into our understanding of the earth system (e.g., deMenocal, 1995; Haug et al., 2001; Zachos et al., 2005; Sluijs et al., 2006), but is limited by subduction to (primarily) the Cretaceous and younger record. Continental drilling lays open earth's archive extending to the far depths of deep time preserved on the planet – the Archean. Vast stores of undeformed sedimentary sections dating from throughout the Phanerozoic and into the Precambrian lay preserved across the stable cratons of the world.

Perhaps most critically, albeit a great treasure of climatic data, the ocean record exhibits a limited dynamic range of response to climate change in that the effects are buffered by the vastness of the ocean system. In contrast, the continental record exhibits an extremely broad range of environmental and climate states, capturing local, regional, and global conditions tied to the history of life on land, in freshwater, and in marginal seas: the full dynamic range of climate change. In light of the land-based existence of our species, documenting the regional and even local responses to global changes in continental (and epeiric sea) regions is critical to documenting the biotic responses to climate change.

Table A1. Key to proposed drill sites map (see Fig. 1).

1 Stoneman Lake, Arizona Paleoenvironments Drilling Project (proponents: R. S. Anderson, P. Fawcett, E. Brown, J. Werne, D. Kaufman, G. Jiménez-Moreno, J. Geissman, M. Ort)

2 Trans-Amazon Drilling Project: History of the Neotropical Rain Forest (proponents: P. Baker, S. Fritz, D. Battisti, B. Horton)

3 African Late Pleistocene Biotic and Environmental Revolution (ALBER) (proponents: R. Bernor, M. Fortelius, L. Rook, X. Wang, G. Woldegabriel)

4 Drilling the Late Miocene Höwenegg *Lagerstätte*, Hegau, southern Germany (proponents: R. Bernor and A. Kaufman)

5 The Lago de Tota Drilling Project (proponents: B. Bird, J. Escobar, P. Pollisar, M. Velez)

6 Kings River Alluvial Fan Terrestrial Drilling (KRAFTD) (proponents: M. Brady, C. Johnson, P. Van de Water, B. Weinman)

7 Drilling to Elucidate Causes of Extinction During the Oceanic Anoxic Event at the Cenomanian/Turonian Boundary (proponents: T. Bralower, M Arthus, M. Fantle, L. Kump, M. Follows, J. Sepulveda, R. Leckie, B. Sageman)

8 The Arctic in a Greenhouse World: Drilling within a Cretaceous Deep Time Observatory (proponents: K. Chin, D. Harwood, R. DeConto, M. Pagani, and S. Warny)

9 The Terrestrial Greenhouse to Icehouse Transition (Eocene–Oligocene) of the Northern Great Plains (proponent: D. Terry)

10 Pennsylvanian Cyclothems of the Paradox Basin (proponents: B. Dyer and A. Maloof)

11 Project EOCore (proponents: R. Fluegman, J. Grigsby, K. Miller, J. Wright, M. Katz, B. Wade)

12 ANDRILL Coulman High Project: CO_2, Thresholds of Past and Future Ice Sheet Behavior (proponents: D. Harwood, R. Levy, B. Luyendyk, F. Rack, A. Shevenell, ANDRILL Science Committee)

13 Argentina Loess Sequences (proponent: C. Heil)

14 Eoarchaean Tidal Signatures in the > 3.7 Ga Isua Greenstone Belt, Greenland (proponents: L. Hinnov and N. Nofffke)

15 Cretaceous Microfossil *Lagerstätte* from Coastal Sections in Tanzania (proponents: B. Huber and K. MacLeod)

16 Drilling the Ediacaran–Cambrian Transition in South China (proponents: A. Kaufman and S. Xiao)

17 ONSET: Observing the Neoproterozoic Snowball Earth Transition (proponents: F. Macdonald, M. Schmitz, C. Dehler, T. Bosak, P. Cohen, S. Pruss, D. Johnson, A. Brandon, R. Simmons, K. Karlstrom, D. Condon, G. Halverson, A. Prave, and M. Zhu)

18 US Participation in the "Return to Mochras: A New Global Standard for Early Jurassic Earth History" (proponents: K. Miller, J. Browning, L. Hinnov, and K. Williford)

19 "Blue Sky" Geology-Core Drilling in the Unstudied Grove Center Late Paleozoic Outlier in Western Kentucky (proponents: S. Elrick and W. J. Nelson)

20 Colorado Plateau Coring Project (proponents: P. Olsen, D. Kent, J. Geissman, R. Mundil, G. Bachman, R. Blakey, W. Kürschner, and J. Sha)

21 Environments of Tropical East Africa since the Late Miocene: Continental Drilling in Lake Tanganyika (proponents: M. McGlue, J. Russell, E. T. Brown, I. Castañeda, A. Cohen, C. Ebinger, S. Ivory, T. Johnson, C. Scholz and members of the 2012 PAGES/NSF East African Drilling Workshop)

22 Recovering a 3 to 5 Million Year Paleolimnological Record from Butte Valley, California (proponents: A. Smith, E. Ito, J. Werne, J. Feinberg, C. Whitlock, and D. Adam)

23 Documenting Tropical Climate During Earth's Last Icehouse Collapse: The Permian of Western Equatorial Pangaea (proponents: G. Soreghan, K. Bennison, W. DiMichele, T. Rasbury, N. Tabor, and N. Heavens)

24 Drilling Through Holocene Fossil Reefs on the Caribbean Coasts of Panama and Columbia to Document Geochronology, Pristine Reef Paleobiology and Paleo-sea-level (Geophysical) Significance in an Unstudied Subequatorial Region (proponents: M. Toscano, J. González, A. O'Dea, J. Lundberg, I. Correa, and H. Mora)

26 Potentially Extensive Plio-Pleistocene Earth System Records at Yardi Lake (proponents: G. Woldegabriel, S. Ambrose, B. Asfaw, A. Asrat, R. Bernor, J.-R., Boissieri, T. Endale, H. Gilbert, W. Hart, H. Lamb, P. Renne, F. Schäbitz, M. Trauth, and T. White)

26 Post-eruptive Maar Sediments from the Giraffe Kimberlite: Potential for a World-Class Continental Record of Middle Eocene Paleoclimate from Northern Canada (proponents: A. Wolfe, and P. Siver)

27 Building a High-Resolution History of Mono Lake from yesterday to 760 kyr BP (and beyond?) (proponents: S. Zimmerman, S. Hemming, A. Deino and Team Mono)

28 Records of Glacial Advance, Retreat, and Large-Scale Deglacial Flooding in Central North America (proponent: B. Curry)

29 The Early Eocene Lacustrine Green River Formation (proponents: M. Machlus, S. Hemming and S. Bowring)

30 Outpacing the Anthropocene: The case for a rapid release of carbon at the Paleocene–Eocene Thermal Maximum (proponents: M. Schaller and J. Wright)

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Scientific Drilling
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A plan for a 5 km-deep borehole at Reykjanes, Iceland, into the root zone of a black smoker on land

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Abstract. A summary workshop report describing the progress made so far by the Iceland Deep Drilling Project (IDDP) is presented below. The report provides recommendations concerning technical aspects related to deep drilling, and invites international participation in both the engineering and the scientific activities of the next phase of the IDDP. No issues were identified at the workshop that should rule out attempting the drilling, sampling and testing of the proposed IDDP-2 well. Although technically challenging, the consensus of the workshop was that the drilling of such a hot deep well, and producing potentially hostile fluids, is possible but requires careful contingency planning. The future well will be explored for supercritical fluid and/or superheated steam beneath the current production zone of the Reykjanes geothermal field in SW Iceland. This deep borehole will provide the first opportunity worldwide to directly investigate the root zone of a magma-hydrothermal system which is likely to be similar to those beneath the black smokers on the world-encircling mid-ocean rift systems.

1 Introduction

Ninety-four engineers and scientists attended a workshop on the Iceland Deep Drilling Project (IDDP) from 3 to 5 September 2012, at Svartsengi, SW Iceland to discuss (i) the lessons learned from the first IDDP-1 exploratory borehole, in 2009 at the Krafla Volcano in NE Iceland, and (ii) plans to drill and study a new 4–5 km-deep borehole, IDDP-2, at Reykjanes, which is planned to be drilled in 2014–2015 at the SW tip of the island where the Reykjanes Ridge emerges from the Atlantic ocean (Fig. 1).

The workshop was funded by the International Continental Scientific Drilling Program and by the IDDP. The participants were from Iceland, Canada, France, Germany, Japan, Italy, Netherlands, New Zealand, Norway, Switzerland, UK, and USA, including several students and young researchers who presented their ongoing work relevant to the IDDP.

Since 2000 the Iceland Deep Drilling Project has planned to drill three 4–5 km-deep holes into the roots of three different high-enthalpy geothermal systems in Iceland. The workshop in September 2012 was the ninth in a series of IDDP workshops since 2002. An early key outcome was the IDDP Feasibility Report (2003, http://www.iddp.is), reporting on (1) geosciences, (2) drilling techniques, and (3) fluid handling and evaluation. One of the chief conclusions of that report was that a well that produces supercritical fluids should have a greatly enhanced power output relative to conventional high-temperature geothermal wells. This initial study identified three locations: Krafla, Hengill (Nesjavellir) and Reykjanes, (see Fig. 1) as being suitable locations to site deep wells to produce supercritical geothermal fluids. The concept was that at each site the geothermal industry would drill and case a 3 or 3.5 km-deep well that would then be deepened by the IDDP consortium to investigate the system below and explore for supercritical fluids. A short paper on the concept of the IDDP itself (Friðleifsson et al., 2013) is included in a special issue of Geothermics which we expect will be published this year.

In common with most high-temperature geothermal systems in Iceland, the systems at Krafla and Hengill contain

Figure 1. The slow spreading ($2\,\mathrm{cm\,a^{-1}}$) Mid-Atlantic Ridge (MAR) connects with central neovolcanic rift systems of Iceland (dark blue). Black circles are high-temperature geothermal systems. RVZ = Reykjanes Volcanic Zone; EVZ = Eastern Volcanic Zone; NVZ = Northern Volcanic Zone. The SSZ = Southern Seismic Zone and TFZ = Tjorness Fracture Zone. The white areas are glaciers.

Figure 2. Oblique aerial view looking NE of the Reykjanes Peninsula showing the location of the Reykjanes Geothermal Field (steam plume in center) and the Svartsengi Geothermal Field in the far distance (upper right). Note the ridges of hyaloclastites surrounded by Holocene basaltic lava flows.

dilute geothermal fluids, only slightly modified by water/rock reactions and the possible admixture of some magmatic gas. In contrast, and in keeping with its location on a narrow peninsula surrounded on three sides by the Atlantic Ocean, the Reykjanes system contains hydrothermally modified seawater. The economic motivation behind the Iceland Deep Drilling Project (IDDP) is that deeper geothermal wells that penetrate higher enthalpy resources, capable of producing supercritical fluid, have the potential to greatly enhance the power output of geothermal fields without enlarging their size and environmental footprints (Friðleifsson and Elders, 2005). The first IDDP well, the IDDP-1, was drilled in the Krafla – a caldera in NE Iceland. It was intended to explore for supercritical geothermal resources at 4.5 km depth, but had to be terminated at only 2.1 km depth when it encountered molten rhyolite magma (Elders et al., 2011). The well was controlled by circulating cold water as drilling mud. It was completed as a production well, with an inner sacrificial casing cemented inside a production casing, and with a perforated liner to the bottom of the well. It was cooled extensively for about 2 months, and after many months of thermal recovery it was flow tested for more than 2 yr. It soon became clear that we were dealing with the world's hottest geothermal well, with wellhead temperatures up to 450 °C and wellhead pressure about 145 bar. The superheated steam produced from the well is sufficient to generate some $35\,\mathrm{MW_e}$.

Because the Reykjanes peninsula (Fig. 2) is the landward extension of the Mid-Atlantic Ridge there is widespread interest within the scientific community in this drilling project. As the geothermal fluid at Reykjanes is modified seawater, this deep borehole will provide the first opportunity worldwide to directly investigate the root zone of a magma-hydrothermal system which is likely to be similar to those beneath the black smokers on the world-encircling mid-ocean rift systems. A complete ICDP-IDDP Workshop Report 2012 is provided at http://www.iddp.is.

2 Well IDDP-1 at Krafla

In 2006, the operator of the Krafla Geothermal Field offered to drill a deep borehole, called the IDDP-1, that was designed to reach supercritical conditions. Krafla lies near the northern end of the central rift zone of Iceland, within a volcanic caldera, where a $60\,\mathrm{MW_e}$ geothermal electric plant is currently operating (Fig. 1). Eruptions of the Krafla volcano are episodic occurring at 250 to 1000 yr intervals, with each episode lasting 10–20 yr, the most recent one took place from 1975–1984. The presence of a magma chamber beneath the caldera at 3–7 km depth was inferred from S wave attenuation during the 1975–1984 eruptive episodes. More recently this was confirmed by an MT-TEM survey. Basaltic rocks in the main reservoir are altered to epidote-actinolite mineral assemblages, and temperatures can reach 340 °C at depths as shallow as 2 km. Produced geothermal fluids are dilute solutions of meteoric origin modified by reaction with hot basalts.

In 2009 the borehole IDDP-1 was drilled near the center of the Krafla caldera, a site chosen because supercritical conditions were thought to be likely at 4 km depth. The IDDP-1 well was situated above what was interpreted to be a depression between two shallow lobes of low resistivity in an MT-TEM model, where the depth to a brittle-ductile boundary was estimated to be close to 4.5 km depth (Friðleifsson et al., 2013). In the spring of 2009 drilling had progressed without problems to 2 km depth, where the deepest rocks recovered were mostly unaltered basalt dikes and irregular lenses of felsite. In the next 100 m multiple acute drilling problems occurred. The drill bit got stuck twice, was cut loose and the well side-tracked two times before the reason for the drilling difficulties became apparent in June 2009. At 2104 m depth the drill bit penetrated molten rhyolite magma, which flowed into the well. In the third attempt the drillers were prepared and decided not to attempt retrieving the drill string but remained in magma with full circulation (~ 70 L s^{-1} of cold water) for some 28 h. Once retrieval was attempted the drill string was loose but the lowest 9 m of the open borehole was filled with chilled volcanic glass. Drilling was terminated and the hole was completed as a production well, cased down to 2072 m (Fig. 3) and cooled for over a month. Evidently the resolution of earlier geophysical studies was not sufficient to identify the magma intrusion that the IDDP-1 penetrated.

Extensive studies of this rhyolite indicate that the estimated temperature of the magma is approximately 900 °C, with a volatile saturation pressure of about 40 MPa, a value between hydrostatic and lithostatic. The very low value of δD in the rhyolitic glass (-121 ± 2 ‰) is remarkably similar to that of hydrothermal epidotes from Krafla geothermal wells and could neither be produced from hydration by local geothermal waters nor by mantle-derived waters; instead the source of its hydrogen is apparently derived entirely from hydrothermal alteration minerals. Thus this rhyolite magma formed in a basaltic volcano by partial melting of hydrothermally altered basalts (Elders et al., 2011; Zierenberg et al., 2013).

It took the IDDP-1 well over 6 months to heat up to ambient temperature before flow testing. The well proved to be highly productive. It became the world's hottest producing geothermal well, with wellhead temperatures of up to 450 °C, shut-in pressure of ~ 145 bars, and enthalpy approaching 3200 kJ kg^{-1}. Production tests at different wellhead pressures indicate that the well would be capable of producing up to 36 MW_e, depending on the design of the turbine system. Unfortunately, however, after two years of flow testing, the well had to be shut down in July 2012 to repair some of the wellhead equipment and to replace the wellhead master valves. At this time it is not clear if this well will be allowed to flow again for power production, or be used for re-injection.

3 Plans for drilling well IDDP-2 at Reykjanes

Planning for the second deep well, IDDP-2 to ~ 3.5 km, to be drilled in the Reykjanes Geothermal Field in SW Iceland is now underway. According to a consensus arrived at in 2006 by the three energy companies, the plan is now that the field operator at Reykjanes, HS Orka hf, is now considering funding and drilling a "well of opportunity", IDDP-2 to ~ 3.5 km.

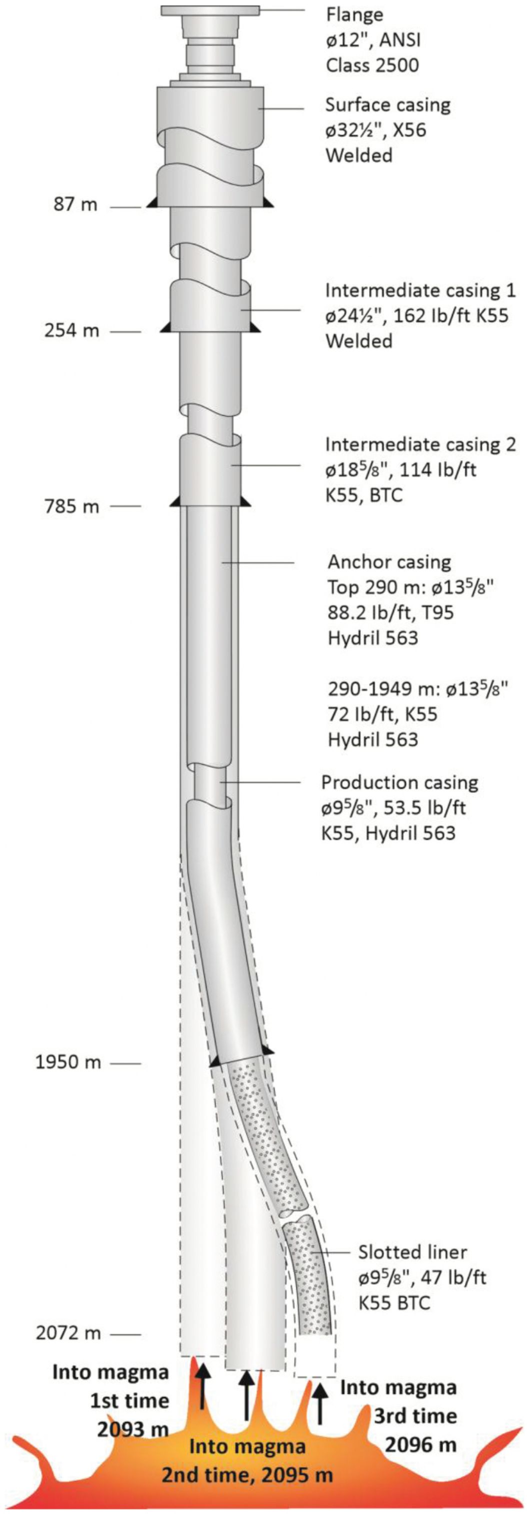

Figure 3. Well IDDP-1 at Krafla as completed.

Then IDDP consortium would fund the deepening and testing of that well to 4.5–5 km. Once again the IDDP is inviting international scientific participation with the international science team again being responsible for obtaining funds for scientific sampling, data collection, and study, both on-site and in the laboratory.

Due to drilling problems encountered in IDDP-1, the cost of drilling of that well in Krafla was very high. The cost of drilling and testing together probably approached about USD 20 million. The HS Orka team is currently re-evaluating the drilling program and cost estimates for the IDDP-2 well at Reykjanes in order to optimize the drilling and testing while lowering the costs significantly. One option would be to scale down the drilling program by drilling and casing a smaller diameter well than the IDDP-1. This re-evaluation is expected to be completed in 2013. It is already quite clear that any expenditure of funds by the international science program will be highly leveraged by the very large contribution by the engineering program of HS Orka hf and the IDDP consortium. It is their funding that will create the opportunity for the science team to participate and the scientists will also benefit from the extensive practical experience and technical capability of the Icelandic geothermal industry.

4 Workshop results

The aims of the workshop were (1) to review the lessons learned from the IDDP-1, (2) to develop the criteria for optimizing the drilling of the IDDP-2, (3) to review the specifics of the site selection, (4) to define the drilling target better, (5) to broaden the scope of international participation and disciplinary range of the science program, (6) to coordinate the engineering and science programs, (7) to develop and coordinate strategies for funding both the IDDP-2 engineering and science activities, (8) to invite broader international and disciplinary participation, and (9) to prepare and distribute a report on the results of the workshop that documents its findings and recommendations, and publicizes the engineering, technical and scientific opportunities that the IDDP-2 offers.

After series of presentations dealing with (1), (2), (3) and (4) above, the workshop participants split up into three main subgroups (Geoscience, Fluid Handling and Drilling) to have more focused discussions about prioritizing the activities that should be performed before, during and after drilling the IDDP-2 deep hole at Reykjanes. By far the largest group was in Geosciences, so for practical reason two discipline-oriented subgroups were formed on diverse geosciences and hydrology. Each breakout group began with 5–10 min presentations relevant to the topic being discussed by the whole group or by subgroups. The following day the breakout groups continued with writing assignments to prepare reports to be submitted to the whole meeting. These reports are part of the SAGA report No. 9, available in full length at the http://www.iddp.is.

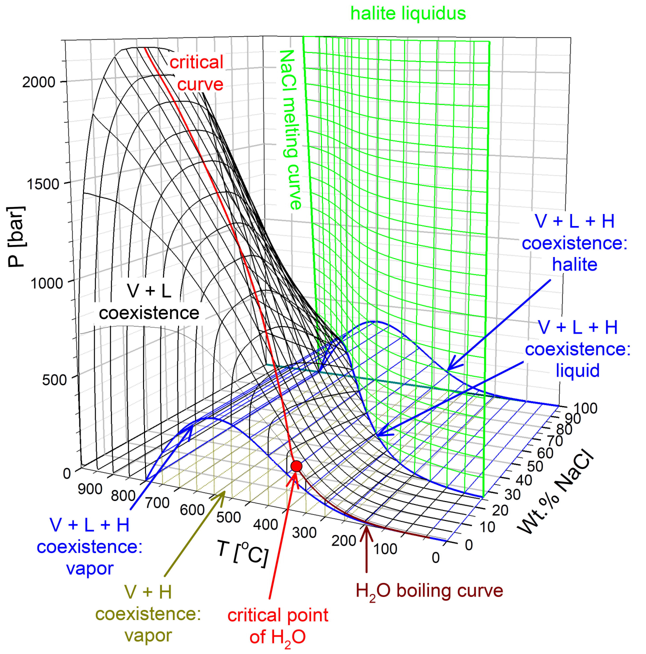

Figure 4. Phase diagram of the system H_2O-NaCl from ambient to magmatic conditions. From Driesner and Heinrich (2007).

Each of the discipline groups concluded by listing (1) the essential, and (2) the recommended and/or desirable geoscience, hydrological, chemical, material, and drilling research and activities that should be undertaken in support of the proposed IDDP-2 well: pre-, during and postdrilling. The Geoscience group began by focusing on the past, recommending that as much information as possible should be obtained and interpreted in the next couple of years ahead of the drilling of IDDP-2 and make use of and gather information from new production/injection wells to refine existing conceptual model of the Reykjanes drill field. A series of recommendations for research and monitoring activities during and after drilling followed. The hydrology subgroups emphasized that the hydrology of saline geothermal systems is significantly more complicated than for dilute water systems. This is because the phase diagram for saline waters is more complex than that for dilute water. It shows a much wider temperature–pressure range between the coexistence of two phase vapor + liquid, and also shows regions of coexistence of vapor + salt and liquid + salt (Fig. 4). Preparation for the IDDP-2 drilling should consider the possible effects of this on achieving the project goals. The group felt that it is essential to develop a series of plausible conceptual models in which complex phase relations are taken into account. These models should cover possible scenarios for the deep parts of the system below the better known part of the reservoir that reaches down to about 2.5 km. Possible scenarios include (see Fig. 5) (i) a tight conductive deep zone below the reservoir formation down to the brittle-ductile transition;

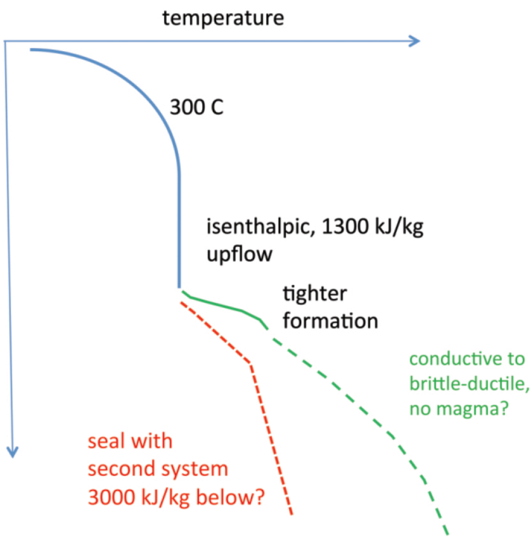

Figure 5. Thermal structure of the up-flow zone for different conceptual models of geothermal systems. Notice difference in thermal structure at depth.

(ii) a tight seal of finite thickness separating the currently exploited reservoir formation from a deeper, supercritical or superheated second reservoir; or (iii) alternative scenarios that need to be formulated based on all available geological and geophysical information. Such models should pay particular attention to the recharge system, the water balance, and the boundaries of system. Possible ways to better constrain these may be obtained from modeling the causes of subsidence patterns, observed trends in vapor fractions, and geophysical survey data.

This was followed by discussion on possible mineralogical and physical methods to better constrain model parameters like temperature and pressure during and after drilling. The hydrology group concluded by recommending that concepts, predictions, and interpretation of data on enthalpy–salinity–pressure relations should be based on phase diagrams for saline fluids (Figs. 4 and 6) rather than approximations based on pure water diagrams.

The fluid handling group began their discussion by emphasizing that they neither knew in advance how high the temperature and pressure will be in IDDP-2 below 4 km depth, nor the composition of the fluid that might be encountered. The wellhead equipment, however, would need to be designed to handle whatever is produced. The best guess on possible temperature–depth profiles need be drawn upon what is known about the overlying presently exploited Reykjanes hydrothermal system. The formation at depth might be *very tight* with a very steep conductive thermal gradient to account for the high rate of heat discharged at the surface. Alternatively, a *sealed zone* might be present, separating the upper convective hydrothermal system from a lower very high-temperature convective system where fluid pressure might be at or above the pressure exerted by a column of fluid extending upward to the surface, as shown in Fig. 5 above.

Given these two contrasting temperature-depth models, different types of fluid could be produced. A reasonable starting point for designing the equipment that must handle the fluid that will be produced is to assume that it will be consistent with the composition of black smoker fluids, extrapolated to the temperature and pressure of the sub-sea reaction zone. These fluid compositions have been examined experimentally by basalt–seawater reaction at the anticipated (T, P). The expected pH's are approximately 4.0–5.5 which is near neutral at the in situ conditions. In contrast, there also is a possibility that highly saline brines might be present beneath the presently exploited hydrothermal system at the Reykjanes Peninsula, formed as a result of repeated subsurface injections of basaltic dikes into rocks bearing fluids initially of seawater composition. The brine produced by this mechanism would be very dense, and tend to migrate downward and accumulate above the transition zone from brittle to plastic conditions. The separated "steam" phase would migrate upward, possibly accumulating beneath an overlying self-sealed zone. Such a "steam" phase would carry some salt and a significant amount of silica. A discussion of how such a self-sealed zone might form and persist in an environment of regional extensional faulting is beyond the scope of the present discussion of the handling of fluids that might be produced from the IDDP-2. The important point is that if a relatively low density, salt-bearing and silica-rich "dry steam" phase is encountered and produced, that fluid is likely to carry a high concentration of non-reactive HCl°, formed by the hydrolysis reaction of salt with water at high temperature and a relatively low pressure. There will be silica precipitation and erosion problems, irrespective of whether black smoker-type brine is produced, or whether a very high enthalpy dry steam phase is produced. In conventional liquid-dominated hydrothermal systems, at temperatures below about 350 °C, low pH prevents polymerization and precipitation of silica. It is not known whether silica precipitation from black smoker-type brines at greater than 400 °C might be inhibited by the natural low pH of such fluids. In the event that dry steam is encountered at > 400 °C, the experience from IDDP-1 should provide insights about how to deal with silica precipitation in that environment. Furthermore, it appears that the most likely fluid that will be encountered in IDDP-2 will be very high-temperature black smoker-type brine. If so, scaling as a result of precipitation of various metal sulfides could be a major problem. If possible, production should be carried out at conditions that prevent metal sulfide scaling in the well, and so induce maximum scaling in a sacrificial portion of surface piping. But, without information regarding the actual composition of the fluid that will be encountered in IDDP-2, the importance of metal sulfide scaling is speculative. Nevertheless, because the likelihood of producing black smoker-type brines is high, computer modeling of the behavior of dissolved metals in such brine during

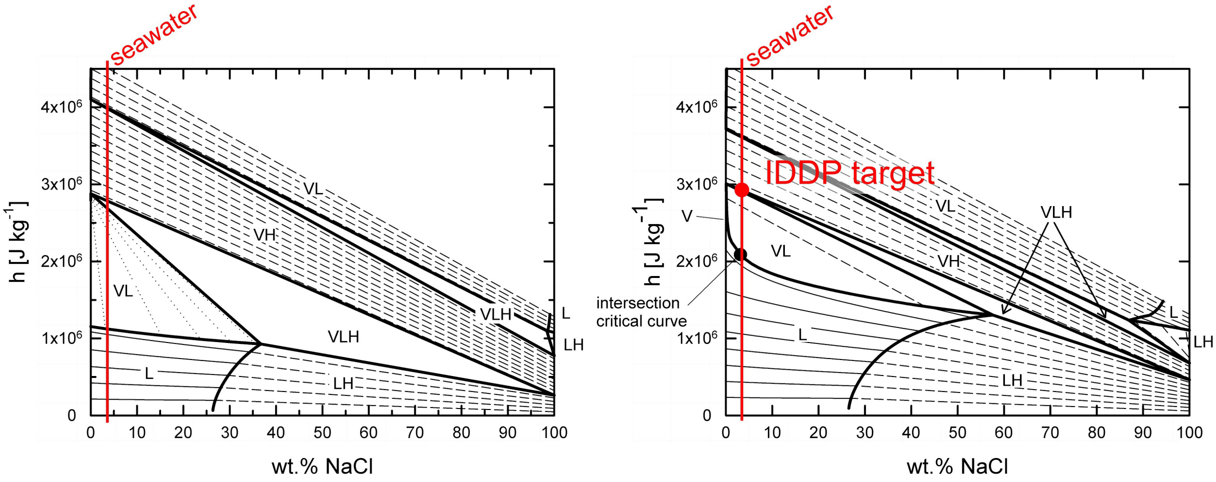

Figure 6. Enthalpy–salinity diagrams for geothermal conditions. Thin solid lines: isotherms in single-phase regions; dashed: isothermal tie lines in two phase regions. Based on Driesner (2007).

production should be undertaken soon, as a guide to methods of dealing with the problem of metal sulfide scaling. Finally, there is a potential for intercepting high levels of hydrogen sulfide, and fluids with high levels of toxic metals, so the hazards of fluid production and disposal need to be considered in advance of drilling. The fluid handling group concluded by emphasize a few items during the IDDP-2 operations such as (i) personnel safety, (ii) well integrity and (iii) that reservoir fluids uncontaminated by drilling fluids should be sampled. This was followed by listing up high priority items before, during and post drilling.

The Drilling Breakout Group emphasized that a comprehensive report on the drilling of IDDP-1 (Lesson Learned) was currently in progress by IDDP. That report should be comprehensive and the drilling group recommended its completion to aid in the planning of the IDDP-2. That report, and the analysis of the failure of the well-head valve on IDDP-1 should then supersede the discussions presented at the workshop. The group then listed several key items as follows:

i. *Safety*: as was demonstrated, the IDDP-encountered higher T and P than had been drilled previously. Also fluid with extreme corrosion and erosion potential could be met and dealt with. This would present drilling difficulties and challenges for standard materials, well designs and fluid handling protocols. On the other hand, these technical and safety challenges present opportunities for the improvement of materials and techniques that can then be applied to the exploration and commercial developments of the roots of geothermal systems worldwide.

ii. *Technical success*: IDDP-2 must be completed as a well that will be expected either to produce geothermal energy for 10 years or more, or to serve as an injection well. In addition, the well should be designed and built to collect the scientific samples and data required by the IDDP. The drilling group accepted the casing plan that had already been established for the IDDP-1 with significant redundancy. However, there are several areas where improvement of equipment and materials will be required for project success. Lessons learned from IDDP-1should be applied to the design of IDDP-2 and management of drilling operations to mitigate risk.

iii. *"The Lessons Learned report from the IDDP-1"* should be finished as soon as possible. When drilling into frontier environments, the drilling engineers are relying on the geologic models of temperature, pressure and fluid compositions. When unexpected conditions are encountered, the well design may not work as planned. In particular, careful analysis should be given to casing design, cementing procedures, the well head and selection of the appropriate materials. In addition, a clear management plan specifying roles and responsibilities should be established to streamline the decision process.

At the conclusion of the workshop conveners had a joint meeting of the SAGA committee and Deep Vision to discuss its outcome and implications. The most important outcome is that none of the wide ranging discussions of drilling, fluid handling, and geoscience identified "critical project issues" that should cause abandonment of the project. Producing much higher enthalpy geothermal fluids from the deeper, hotter, potentially supercritical zone, beneath the producing geothermal reservoirs in Iceland remains an attractive target. However drilling and testing these exploratory boreholes will be technically challenging and expensive. The experience gained from the IDDP-1 well reinforced the truism that drilling leads to surprises, requiring careful contingency planning. Better definition of the conditions in the target zone is a basic requirement for such planning. The discussions at the workshop and the activities suggested before drilling will reduce risk, and put plans for the IDDP-2 on a more confident footing.

The consensus of the geoscience and fluid handling groups is that at depth the Reykjanes system is most likely to be similar to the conditions underlying the high temperature hydrothermal vents (black smokers) on the Mid-Atlantic Ridge. Several vents at 5° S on the Mid-Atlantic Ridge produce supercritical fluids, more dilute than seawater, with temperatures measuring up to 464 °C. Many marine high-temperature hydrothermal vents on different mid-ocean ridges emit fluids with salinities either higher or lower than that of seawater, so that phase separation of supercritical dilute and hypersaline fluids must be an important process in fluid circulation beneath the worldwide mid-ocean ridges. However this does not guarantee that supercritical fluids will be reached by the IDDP-2 well. This depends not only on the fluids and temperature gradients encountered, but also on the nature of the permeability that controls fluid circulation. Fracture permeability is, in turn, affected by earthquake activity, by self-sealing, and by transitions to ductile behavior with depth.

The discussions and suggestions from both the engineering and scientific participants were very wide ranging and to implement all of them would have been unrealistic in terms of available time, resources, and personnel. In response to the workshop, a major challenge facing the IDDP is to form engineering and scientific planning groups to guide the way ahead, by prioritizing the essential activities necessary to advance.

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Mochras borehole revisited: a new global standard for Early Jurassic earth history

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1 Introduction

The Early Jurassic epoch was a time of extreme environmental change: there are well-documented examples of rapid transitions from cold, or even glacial, climates to super greenhouse events, the latter characterized worldwide by hugely enhanced organic carbon burial, multiple large isotopic anomalies, global sea-level change, and mass extinction (Price, 1999; Hesselbo et al., 2000; Jenkyns, 2010; Korte and Hesselbo, 2011). These icehouse–greenhouse events not only reflect changes in the global climate system but are also thought to have had significant influence on the evolution of Jurassic marine biota (e.g. van de Schootbrugge et al., 2005; Fraguas et al., 2012). Furthermore, the events may serve as analogues for present-day and future environmental transitions.

Although our knowledge of specific global change events within the Early Jurassic is rapidly improving, such as the Toarcian oceanic anoxic event (or T-OAE), we still do not have a comprehensive understanding of the timing, pacing, or triggers for these environmental perturbations, principally because of the temporally fragmentary nature of the existing data sets. The major goal for this proposed ICDP project is therefore to produce a new global standard for these key 25 million years of earth history by re-drilling and double-coring a 45 yr old borehole at Mochras Farm on the edge of Cardigan Bay, Wales, and developing an integrated stratigraphy for the cored material. The new data sets will be applied to understand fundamental questions about the long- and short-term evolution of the earth system. Cycles that occur regionally and that provisionally appear in the Mochras logs will allow evaluation of the extent to which major environmental change events are astronomically forced, resulting from internal system dynamics, or are triggered by deep-earth processes.

2 The first Mochras borehole

The original “Llanbedr (Mochras Farm)” borehole was drilled on the coast of West Wales from 1967 to 1969 (Figs. 1 and 2). Contrary to expectations, a biostratigraphically complete succession of marine mudstone of Early Jurassic age was recovered with a thickness of 1300 m, some 600–1900 m below surface (Woodland, 1971; Dobson and Whittington, 1987; Figs. 3 and 4). This is approximately three times the thickness of the same age strata known from other UK boreholes or from the internationally important coastal exposures. The Mochras succession is also remarkable for the relative uniformity of argillaceous lithology, and the biostratigraphy is relatively well known. Although the borehole succession

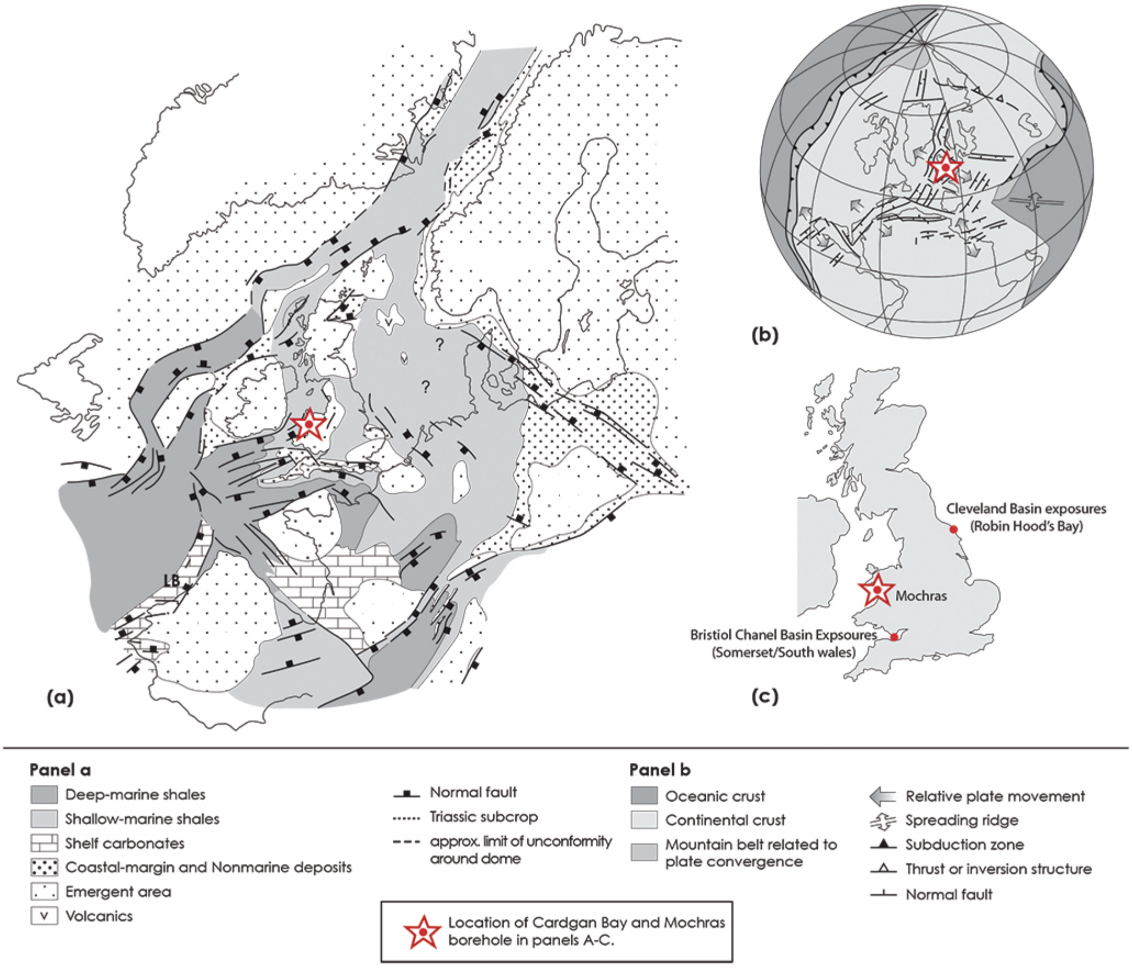

Figure 1. Palaeogeographic setting of the first Mochras borehole (modified from Coward et al., 2003).

has figured prominently in discussions of regional Jurassic palaeogeography and basin development (Holford et al., 2005), drilling predated modern drilling and logging techniques and the advent of chemostratigraphy and cyclostratigraphy, and as a result the true potential of this section to shed light on global processes and history has never been realized. The existing log suite comprises only total gamma ray, spontaneous potential, resistivity (laterolog), neutron, density, and sonic, and these logs were run to a limited depth of 1300 m (or down only to mid-Sinemurian strata). There are no logs for the Hettangian and early Sinemurian stages and very sparse log data for the Toarcian (see Fig. 3).

3 Workshop participants and programme

Recognizing the potential for realizing a transformative understanding of climate changes between extremes, the ICDP funded a workshop to plan future drilling at Mochras. The workshop participants comprised thirty-two researchers from China, Denmark, France, Germany, Hungary, the Netherlands, Poland, Switzerland, the UK and the USA. These participants also represented the wider interests of another ten scientists who have expressed an interest in the project but were unable to attend the meeting, including colleagues from Argentina. The workshop was held from 16 to 23 March and comprised a field excursion to the Cleveland Basin, core viewing at the British Geological Survey core store at Keyworth, Nottingham, two days of discussion in Oxford, and a supplementary field excursion to the Bristol Channel basin.

4 Field excursions

The field excursion to the Cleveland Basin, Yorkshire (Fig. 1), provided an opportunity to inspect the closest available outcrop analogue for the succession of late Sinemurian to late Toarcian age at Mochras, albeit in a much thinner and more sand-rich succession. Additionally, the Yorkshire coastal exposures include classic exposures of the Jet Rock, the archetypical expression of the Toarcian oceanic anoxic event in NW Europe.

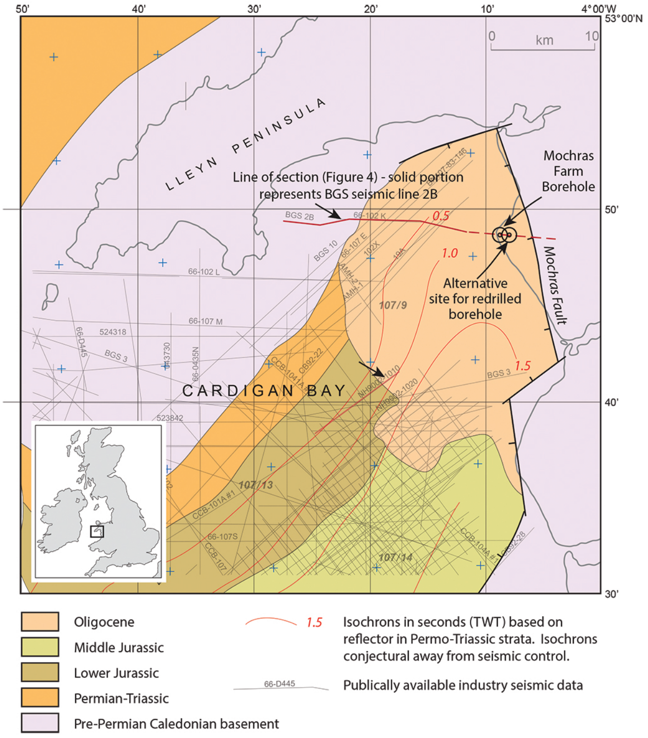

Figure 2. Simplified offshore and onshore geological map for the Cardigan Bay area showing existing and alternative borehole sites together with publically available seismic reflection survey data (based on Dobson and Whittington, 1987; Tappin et al., 1994; British Geological Survey 1 : 25 000 map of Cardigan Bay, Solid Geology).

The first day of the field programme began with an overview of the depositional setting, and then focussed on the late Sinemurian to early Pliensbachian succession of Robin Hood's Bay whilst the second day concentrated on the Pliensbachian–Toarcian transition at Staithes and Port Mulgrave. The party inspected a large normal fault in the southern end of Robin Hoods bay with about 300 m of throw. Remarkably little deformation of the shale successions is present 10 m from the fault.

In Robin Hood's Bay, two putatively global black shale "events" are exposed in the section, the older around the *Oxynoticeras oxynotum* ammonite zone, and the younger at the Sinemurian–Pliensbachian boundary. Both events are expressed in significant faunal or floral changes and perturbations of the global carbon cycle (Korte and Hesselbo, 2011; Riding et al., 2013) and the Robin Hood Bay section serves as the Global Stratotype Section and Point (GSSP) for the base of the Pliensbachian Stage (Meister et al., 2006; Fig. 5a). Although the Robin Hood's Bay section represents one of the best-characterized successions in the world for the stage boundary, it is notable that the basal ammonite biozone of the Pliensbachian in Mochras is double the thickness of the same zone in Robin Hood's Bay, emphasising the global importance of additional sampling of the Mochras succession.

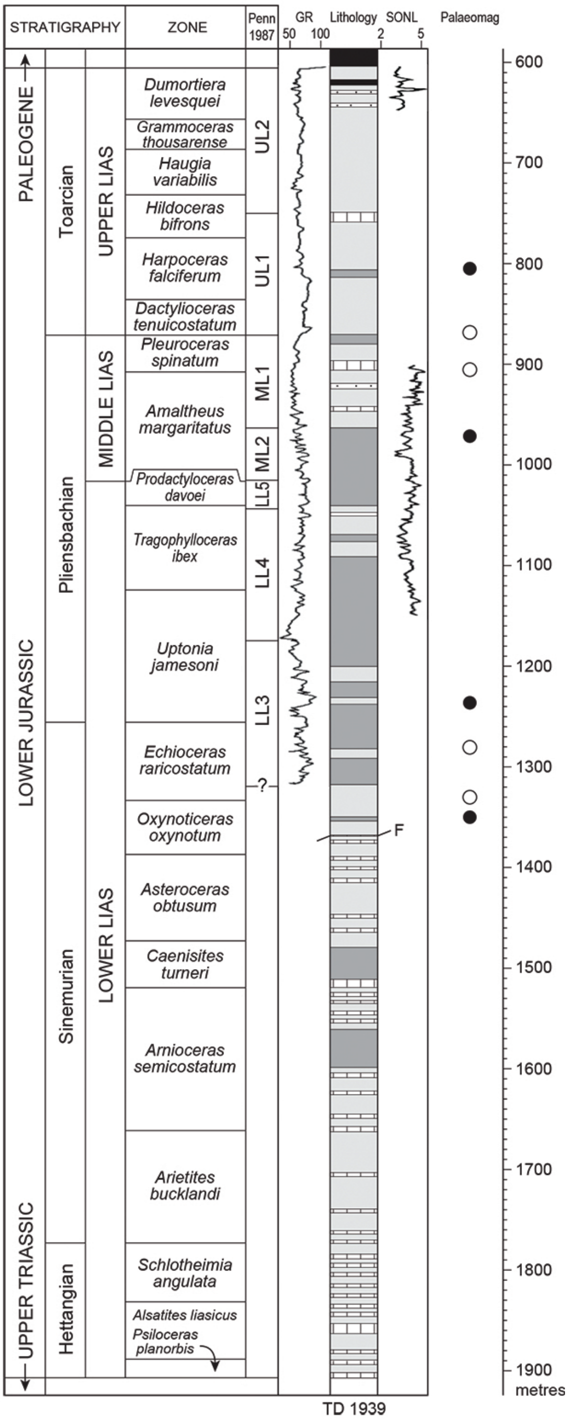

Figure 3. Summary stratigraphy for the first Mochras borehole showing complete representation of Early Jurassic ammonite zones (modified from Tappin et al., 1994). Also indicated are the palaeomagnetic polarities from pilot studies of MacNiocaill and Robinson (unpublished data). Lithology: black – conglomerate, grey – silt/mudstone, light grey mudstone, dots – sandstone, bricks, limestone, TD – terminal depth, F – fault, GR – gamma-ray log, SONL – sonic log, black dot – normal polarity, white dot – reversed polarity.

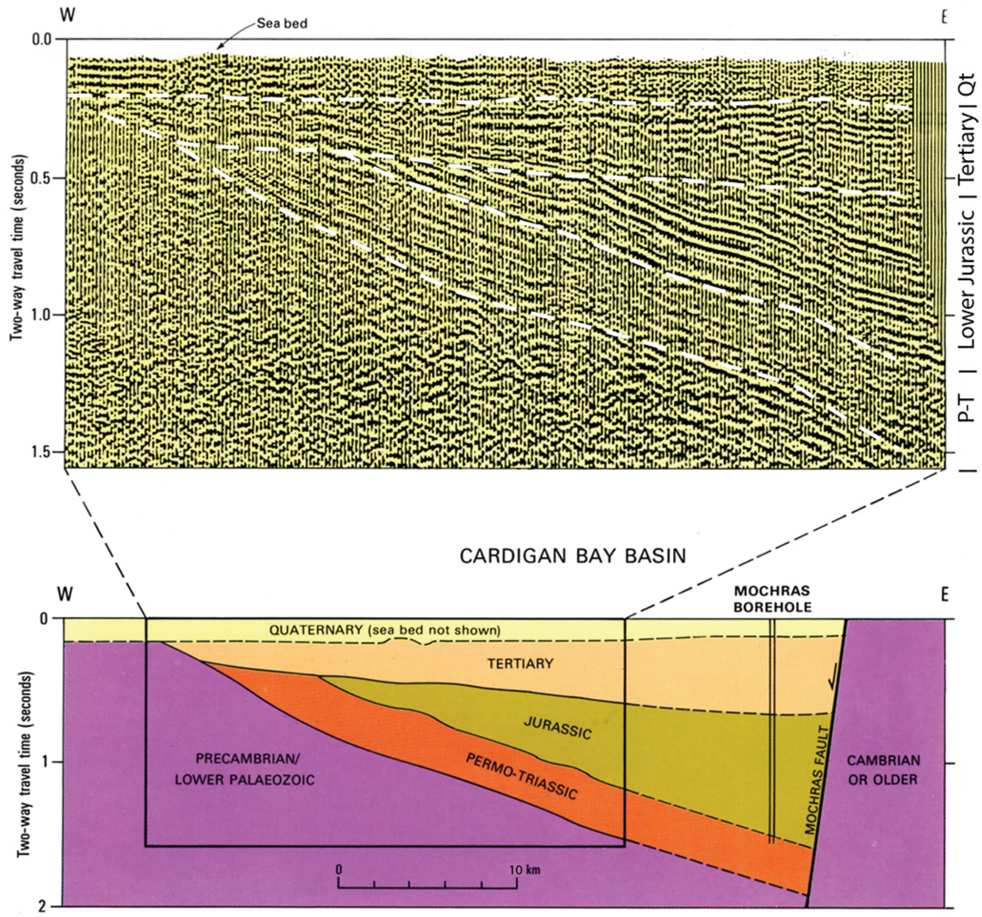

Figure 4. British Geological Survey seismic reflection profile 2B and extended geological interpretation including original Mochras borehole (from Tappin et al., 1994, with minor modification).

A prime research goal for the Mochras project is the construction of a robust astrochronology for the entire Early Jurassic. The field excursion allowed discussion of previous cyclostratigraphic studies based on stratigraphically limited intervals of the Cleveland Basin succession. In particular the early Pliensbachian interval has been a target for earlier attempts to recognize regular cycles (Van Buchem et al., 1994); the same interval has been shown to be regularly cyclic in widely spaced UK outcrops and in the Mochras core (Weedon and Jenkyns, 1999; R. Morgan, unpublished student project, Oxford). Additionally, other intervals exposed in the Yorkshire cliffs, such as the mid-Sinemurian interval, appear to be regularly cyclic, but have never been systematically studied (Fig. 5b).

Methane seep mounds have been described recently from several Early Jurassic mudrock successions worldwide and have been shown to have a distinctive carbon-isotopic signature (e.g. Allison et al., 2008; van de Schootbrugge et al., 2010). The field party made a serendipitous discovery of previously undescribed methane seep carbonates in the interval above the Jet Rock at the southern end of Robin Hood's Bay (Fig. 5c). The impact of coeval methane seeps on local carbon-isotope signatures is an important topic to explore as there is a potential impact on use of carbon-isotope time series for cyclostratigraphic analysis and global correlation.

The transition from shallow-water and generally cold-climate sandstone and ironstone of the late Pliensbachian into the deep-water super-greenhouse organic-rich shale of the T-OAE is exposed around Port Mulgrave (Fig. 5d). This part of the succession in Yorkshire is also half the thickness and stratigraphically less complete than the equivalent succession at Mochras. Very large excursions occur in all isotopic systems previously investigated across the T-OAE, and the party discussed the most recent data from systems that respond to local, regional and global changes in ocean redox conditions (e.g. Pearce et al., 2008; Gill et al., 2011). Also clear from the field excursion was cyclicity expressed in lithofacies and ichnofacies, which provides an immense wealth of data for palaeoenvironmental interpretations.

The supplementary field excursion to the Bristol Channel Basin in west Somerset (Fig. 1) examined the carbonate-rich marine mudstone facies of the Blue Lias Formation, including the record of the Late Triassic mass extinction at St Audries Bay, and the base-Sinemurian GSSP at Kilve. Also discussed was the potential of this facies, closely similar to that of the same age in the first Mochras borehole, to yield a continuous astrochronology, as previously documented by Ruhl et al. (2010).

5 Core viewing

Core from the first Mochras borehole was laid out for inspection and sampling at the British Geological Survey core store at Keyworth, Nottingham. In particular the party focussed on major environmental change events and/or stage boundaries. As well as visual description, it was possible to take samples for geochemical pilot studies. Because the core is over forty years old, oxidation of reduced phases during storage is a significant impediment to some geochemical analyses, notably analyses dealing with sulfur isotopes. Nevertheless, samples were obtained to generate pilot data sets for various geochemical techniques to document the fidelity of the section for detailed studies in the proposed core hole. The palaeontological collections were inspected and latex casts taken of the key fossils for more precise identification. The original core had been extensively broken for palaeontological sampling soon after drilling, and the resulting fragments aggregated into stratigraphically crude intervals ranging up to about half a metre. On the other hand, some core that had been previously thought to be missing was rediscovered, such as some early Hettangian strata and including core across the Triassic–Jurassic boundary. In all some 200 samples were collected for further work. In addition, the downhole log paper plots were scanned at high resolution and will be digitized for cyclostratigraphic analysis.

Visual inspection of the core shows that diverse and variable trace fossil assemblages and lithofacies are present, allowing sophisticated interpretations of palaeoenvironmental change to be made through the entire cored interval. Combined with palaeoecological analysis, the Mochras core clearly has the potential to yield an extended record of sea-level change.

6 Oxford workshop

The Oxford workshop initially tackled the first-order science questions that would be addressed by drilling the new core hole, and then went on to consider the data sets required to meet these science goals and the practical challenges to be overcome. Overview presentations provided the logistical and theoretical background for project planning.

The workshop endorsed the view that a new Mochras core will give an exceptionally continuous record of environmental change (broadly defined), combined with an unrivalled integrated timescale. This combination will provide unparalleled opportunity for quantitative understanding of the evolution of the earth system and its relationship to

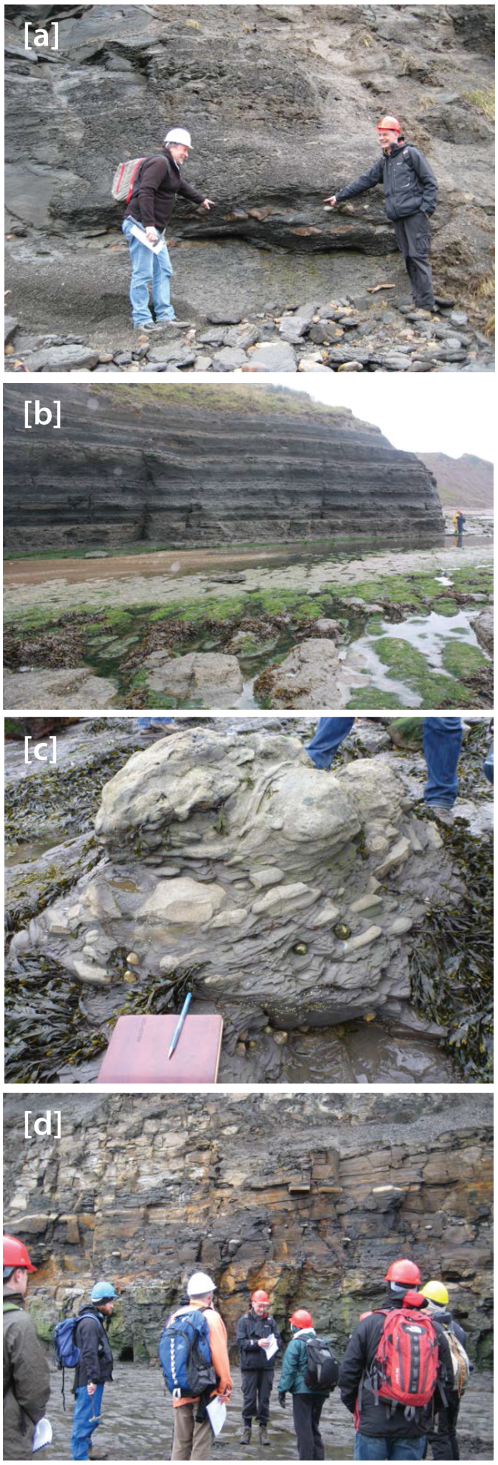

Figure 5. Highlights of the Cleveland Basin field excursion, Yorkshire. **(a)** GSSP for the base of the Pliensbachian Stage (Robin Hood's Bay). **(b)** Potentially regularly cyclic late-Sinemurian succession (Robin Hood's Bay). **(c)** Probable methane seep carbonate mound and concretions in early Toarcian strata (Robin Hood's Bay). **(d)** Exposure of the Jet Rock (record of the Toarcian OAE) at Port Mulgrave.

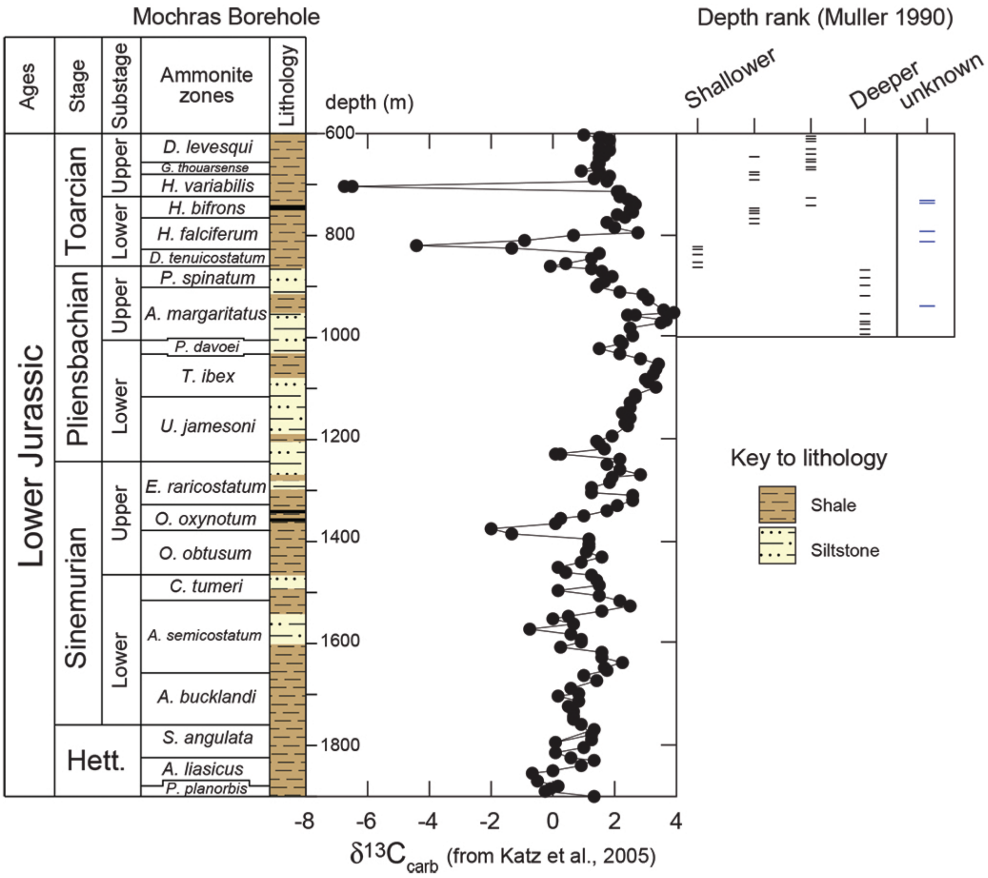

Figure 6. Carbon-isotope profile from bulk carbonate and palaeodepth changes inferred from benthic foraminifers. Modified after van de Schootbrugge et al. (2005). Hett. = Hettangian.

solar system evolution at the point of emergence into the modern world.

Mochras has the potential to provide a global template for Early Jurassic earth systems interaction, an interval of major tectonic change (e.g. supercontinent breakup and formation of the Central Atlantic Magmatic Province or CAMP, one of the largest large igneous provinces), biologic change (e.g. radiation of eukaryotic phytoplankon), and climate change (e.g. the transition from an icehouse to a super greenhouse associated with a major oceanic anoxic event). Such a complete profile with high-resolution stratigraphic framework will provide an invaluable template for correlation of other profiles of that age, including those representing marginal-marine and non-marine facies. Chemostratigraphy and astrochronology should provide a useful tool for such correlation, linking oceanic and atmospheric systems of that time (e.g. Hesselbo and Pienkowski, 2011).

The following science programme was developed at the workshop:

Chemostratigraphy. As demonstrated on the field excursion, several major environmental change events in the Early Jurassic have been documented recently, but are largely unexplored scientifically; some are associated with carbon-isotope anomalies at least as large as that associated with the Paleocene–Eocene boundary (Korte and Hesselbo, 2011; Riding et al., 2013). The Sinemurian–Pliensbachian boundary event is a good example, and shows characteristics akin to the T-OAE, such as increased carbon burial and significant sea-level rise. A crucial requirement for chemostratigraphy – and for the use of geochemical proxies generally – is the preservation of a substrate from which the original chemical attributes of the environment can be extracted and which lack strong diagenetic overprint. Importantly, comparison of the well-characterized carbon-isotope data set from Yorkshire with the low-resolution carbon-isotope data from the original Mochras core, shows that the values in moderately low-maturity organic matter from Mochras (R_0 max = 0.38–0.63; Holford et al., 2005) track changes in the global carbon cycle (Korte and Hesselbo, 2011; van de Schootbrugge et al., 2005; Fig. 6). Thus, a re-drilled Mochras core has the strong potential to provide a global standard high-resolution carbon-isotope stratigraphy for the entire Early Jurassic interval based on marine and nonmarine organic matter and also likely carbonate.

Palaeobiology and palaeoecology. Detailed records of macro- and microfossils can be generated at metre-scale resolution. An understanding of biotic change through the Early Jurassic is possible based on combined analysis of the taxonomy and paleoecology of molluscs (including ammonites), dinoflagellates, pollen, calcareous nannofossils, benthic foraminiferas and ostracods. These data will also form the foundation for the high-resolution biostratigraphic framework required for timescale development and for application of the broad array of results from Mochras to other parts of the world. Benthic foraminiferas and ostracods, previously studied from the first borehole (Johnson, 1975, 1976; Copestake and Johnson, 1984; Boomer and Whatley, 1992), can be used both as ecological indicators of environmental change, and as paleobathymetric indicators of sea level change. Phytoplankton (dinoflagellate cyst and nannofossil) data are essential for describing the early radiation of these groups, and for understanding mechanistic links between primary production and carbon cycling, especially during carbon cycle perturbations such as the T-OAE. Pollen records will document terrestrial floral changes in the aftermath of the end-Triassic mass-extinction, and can be used to reconstruct continental floral changes during times of deoxygenation in the oceans, and will ground-truth records of charcoal delivered to the oceans from forest fire burning.

Macrofossil analysis is possible in core material because of the small size and/or abundance of benthic molluscs during the Early Jurassic, as has been proven in the contemporary Schandelah core, recently drilled in northern Germany. Studies on well-preserved macroscopic ichnofabric will provide important “in situ” data, reflecting changing environmental conditions on the bottom such as food supply, redox, water depth, and sea-level change. Biotic records can also be compared with records of nutrient regime and redox to elucidate the processes driving faunal change.

Astrochronology. Also of marked importance is the potential of Mochras to yield an astrochronology for the time represented by the Early Jurassic, where existing records are fragmentary and of limited time extent. Work on research boreholes drilled through a 500 m thick Late Jurassic mudstone succession in southern England (Kimmeridge Clay) have previously yielded an astrochronological calibration of unprecedented detail, which has been used to define the durations of sea-level cycles and help to calibrate the Kimmeridgian–Tithonian timescale (Huang et al., 2010). New data from a re-drilled Mochras borehole will allow the establishment of a cyclostratigraphic age model that will close the gaps between the older cyclostratigraphies (Olsen and Kent, 1999; Ruhl et al., 2010) and the younger parts of the geological column. The combination of high-resolution chemostratigraphy and astrochronology will provide fundamental insights into the pacing of changes in the mid-Mesozoic carbon cycle, including those occurring during the big environmental change events, and thus help identify their ultimate causes. Pilot cyclostratigraphic studies based on the old geophysical logs were presented or discussed at the workshop (L. Hinnov, C. Huang, R. Morgan, T. Wonik; Fig. 7). Mochras will provide a 25 Myr record of astronomically tuned earth history that in addition to eccentricity and precession includes also the obliquity signal, potentially giving a unique opportunity to test astronomical models of Earth–Mars resonance in deep time. As well as providing an order of magnitude improvement in precision and accuracy of the geological timescale for the Early Jurassic, we can use new Mochras data to test astronomical pacing of icehouse and greenhouse sea level changes in the Mesozoic world.

Magnetostratigraphy. The new core will have great potential for definition of a magnetostratigraphy for the Early Jurassic interval. An accurate magnetostratigraphy is particularly important because it enables correlation not only to marine but also to terrestrial successions, which facilitates the global use of the newly developed Early Jurassic standard in the redrilled Mochras borehole. Although palaeomagnetic studies were undertaken at the time of the original drilling (Woodland, 1971), the sensitivity of modern instruments is now better by a factor of 100. Thus new (oriented) cores have the potential to provide a robust and complete reference magnetostratigraphy calibrated by astrochronology. A pilot study based on the existing core has also yielded very promising results (Fig. 3).

Geochronology and age model. The biostratigraphy, chemostratigraphy, cyclostratigraphy and magnetostratigraphy need to be anchored in an absolute chronological framework. The approach developed will be to construct an integrated age model for the time interval of interest, comprising radio-isotopic dating (U-Pb zircon by ID-TIMS) of stratigraphic sections in Canada and South America; sections that are already well-constrained biostratigraphically and with rapidly improving chemostratigraphy. Quantitative methods should be used for stratigraphic correlation and seriation, e.g. Constrained Optimization/CONOP9, and algorithms for objectively combining the radio-isotopic dates into a high-precision and high-accuracy age model (Sadler et al., 2003; Meyers et al., 2012). The recent EARTHTIME initiative has meant that the U-Pb system is now fully calibrated to standard units and capable of producing dates with uncertainties of the order of 0.15 % (95 % confidence, including ^{238}U decay constant error). This is more than sufficient to resolve the 405 kyr eccentricity band width, and thus the radio-isotopic dating can be used to pin down the floating highly-resolved astrochronology. This absolute chronology will be required to assess the exact temporal relationship of documented environmental perturbations to driving mechanisms (e.g. emplacement of the Karoo LIP at about 183 Ma; Svensen et al., 2012).

Atmospheric composition. Carbon dioxide and oxygen levels in earth’s atmosphere are controlled by biogeochemical feedbacks that take place on million-year timescales. The major disruptions to earth’s carbon cycle represented by OAEs are believed to have interfered with the oxygen content of the atmosphere (Handoh and Lenton, 2003). Forest

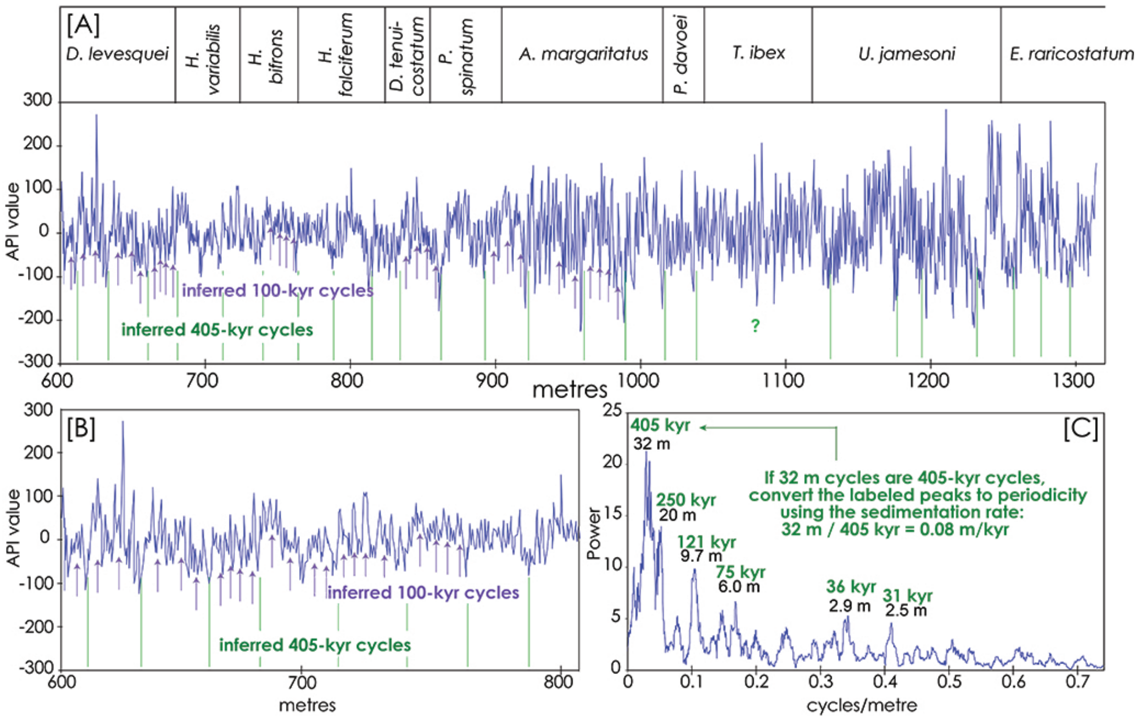

Figure 7. Gamma ray log from the original Mochras borehole, digitized from original analog graphs. **(a)** Entire series after removing a long-term irregular trend. **(b)** Interval from the upper part of the borehole highlighting ∼ 32 m cycling interpreted as 405 kyr cycles, (green) and 6–9.7 m cycles interpreted as ∼ 100 kyr cycles (purple). **(c)** Multitaper power spectrum of the entire gamma-ray log series and preliminary Milankovitch interpretation.

fires require oxygen in order to burn, meaning that forest fire activity is highly sensitive to variations in the abundance of oxygen in the atmosphere (Belcher and McElwain, 2008). There is therefore a record of palaeoatmospheric oxygen in the form of fossil charcoal, which can be used to reconstruct changes in atmospheric oxygen content through this interval, when all existing hypotheses predict that there should have been huge changes.

Seawater oxygenation and nutrient flux. There are many new palaeoceanographic proxies now available specifically for organic-rich and organic bearing mudstones, these include: Mo, Cr, U isotopes for determination of global-regional extent of anoxia; redox-sensitive and pH-sensitive trace metals U, Mo, etc.; highly reactive Fe, and; compound-specific biomarker analysis (e.g. Anbar and Gordon, 2008; McArthur et al., 2008; Pancost and Boot, 2004). These new and developing proxies (e.g. Poulton and Canfield, 2005, 2006) can be applied in conjunction with pyrite petrography (Wignall and Newton, 1998) and SEM, thin section and micro-CT to evaluate the severity and timescales of euxinia (H_2S). Isotopic analyses of pyrite and carbonate-associated sulfur (CAS) can provide important constraints on regional or global changes in the pyrite burial flux and the operation of the oxidative pathway of the sulfur cycle (e.g. Newton et al., 2004, 2011; Gill et al., 2011). These redox studies can then be used to constrain controls on nutrient recycling, thus providing insights into nutrient-redox feedbacks (März et al., 2008). Biomarker records of photic zone euxinia and pyrolitic processes will be used to constrain anoxia in the water column and oxygen concentrations in the atmosphere, respectively. Fresh core material is key to obtain high-resolution inorganic and organic geochemical proxy records.

Palaeoceanography. Palaeogeographically, the location of Mochras is at a critical latitude, influenced both by subtropical and mid-latitude climate and oceanography, and thus very susceptible to astronomical forcing (Ruhl et al., 2010; Bjerrum et al., 2001). At the same time, the transcontinental seaway, linking Tethys to the Boreal Ocean would have strongly influenced the regional oceanography. Currently there is considerable interest in the hydrocarbon industry for understanding palaeoconditions at high northern latitude (source rocks, as well as weathering and climate influence on the development of sand reservoirs). The location of Mochras potentially provides a means to connect our understanding of palaeoceanographic processes on the southern and northern margins of the transcontinental seaway.

Of some significance is better evaluation and understanding of sea-level changes, based partly on a sequence stratigraphic correlation to other profiles representing a variety of facies and environments (Hesselbo and Jenkyns, 1998; Pieńkowski, 2004; Korte and Hesselbo, 2011). Information on sediment provenance and hinterland climate may be extracted from study of detrital clay minerals (e.g. Hesselbo et al., 2009). Clay mineralogy has been successfully used in many Mesozoic palaeoclimate reconstructions, especially as reliable proxy for humidity (Dera et al., 2009). Besides, high-resolution clay mineral analyses will provide another proxy for inferring astronomically forced climate cycles. Electron-beam-based techniques applicable to mudrocks can be used to infer changes in both sea level and climate (improving hugely on early work such as Williams et al., 2001).

Earth system models. The nature of the changes in the carbon, oxygen and nutrient cycles through the Toarcian oceanic anoxic event and adjacent intervals will be a major focus of study. In particular the combination of models, such as those of Bjerrum et al. (2006) and Bjerrum and Canfield (2011), and data from Mochras can be used to test the hypothesis that organic carbon burial during the event caused a rise in atmospheric oxygen that ultimately ended the OAE (Handoh and Lenton, 2003). Associated with this is the idea that transitions between oxic and anoxic states of the ocean are propelled by positive feedback involving phosphorus burial/recycling – recycling is enhanced under anoxic conditions, suppressed under oxygenated conditions.

7 Borehole location and logistical considerations

A detailed coring, logging, and sampling plan was articulated at the Oxford workshop. The core hole will be drilled between the period of October 2015–March 2016 with a large diameter (38–10 cm) core and 9–10 logging runs. The location of the original borehole, adjacent to a now disused military aircraft facility (Fig. 8), means that deployment of the drilling rig will be relatively straightforward. The favoured precise location of the new hole is still subject to the results of geophysical site survey, but the provisional plan is to locate the new hole a few hundred metres inland of the original borehole site, but with a significant slant to avoid fault-related disturbance at depth. A slanted core may also facilitate accurate core reorientation.

Onsite descriptions will consist of minimal measurements (onsite photos, general lithology, grain size, sorting, roundness, bedding, colour, fossil content, ichnofabric, physical structures, cement, accessory minerals, contacts). Cores will be transported to the British Geological Society (BGS) core repository where they will be split into thirds (archive, working, and macrofossil) and scanned (Geotek, XRF, and photoscans). A detailed core description and sampling party (lasting approximately 1 month) of all participants will be held about 6 months after drilling. We anticipate a similar number of samples as that obtained from a typical IODP succession of similar thickness (~ 10 000 samples). The core will be archived at the BGS and data archived in numerous public databases. Scientific papers will have a target date of 2.5 yr after a scientific results meeting (October 2018) in an online, open access journal.

Figure 8. View from close to the first Mochras borehole site (now under sand dunes) looking NE towards the disused airfield at Llanbedr.

8 Summary and next steps

In summary, the workshop highlighted the following unique potential for the Mochras project:

- First biostratigraphically calibrated *magnetostratigraphy* for the entire 25 Myr-long Early Jurassic *based on a single section*.
- High-resolution continuous *cyclostratigraphy* for the Early Jurassic; Astronomical Time Scale (ATS); *Solar System resonance*; *length-of-day* and *tidal dissipation*.
- Multi-proxy *chemostratigraphy* to track supercontinent breakup influence on the global earth system.
- Record of the Triassic/Jurassic *mass extinction* and subsequent *recovery* of the carbon cycle, biosphere and ocean, and effects from CO_2 and other *volatile releases* from the CAMP.
- Early Jurassic *sea level change* and the *icehouse–greenhouse* transition across the Pliensbachian–Toarcian boundary.
- Interdependencies among *primary productivity, microbial metabolisms, nutrient fluxes and ocean redox state*.
- Integrated record of changes in *atmospheric* and *marine* composition understood in the context of quantitative whole earth system models.
- Order of magnitude improvement in knowledge of Early Jurassic geological timescale through full synthesis of *radioisotopic* and *chonostratigraphic* scales.

The workshop identified the crucial next steps as preparation of the full ICDP proposal to be submitted in January 2014, with a parallel programme of site geophysical characterization to guide precise location of the new borehole.

The Mochras Revisited Science Team

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Eger Rift ICDP: an observatory for study of non-volcanic, mid-crustal earthquake swarms and accompanying phenomena

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1 Introduction and goals

What are the physical and chemical processes leading to earthquakes and volcanic eruptions? How does fluid transfer through the earth's crust work? How may geological processes influence the deep biosphere and the evolution of early life at depth? These are questions tackled by the ICDP project and the planned drilling in the Eger Rift region. For several centuries, the West Bohemia (Czech Republic) and the Vogtland regions (Germany) have faced earthquake swarm seismicity and large-scale diffuse degassing of mantle-derived CO_2 (e.g. Horálek and Fischer, 2008). The scientific term "earthquake swarm" (ES) was coined in this area following the 1824 Hartenberg (Vogtland) earthquakes in order to describe the intensive, long-lasting, low-magnitude seismicity felt by the population (Knett, 1899). Since then, earthquake swarms have been recognized in many regions worldwide under different tectonic and volcanic settings. Their mechanism, however, is still enigmatic and not understood. Recently, the potential hazard posed by earthquake swarms was demonstrated during the destructive M_W 6 Aquila 2009 earthquake (Italy), which was preceded by three months of earthquake swarms. Nowadays, it is well accepted that ES are driven by fluid instability in the crust. These may be magmatic fluids for ES at volcanoes, or cold/meteoric fluids for ES in other regions, or mantle-derived fluids passing the brittle-ductile barrier through deep rooting faults (e.g. Becken et al., 2011). In West Bohemia–Vogtland, it is still unknown whether magma, water, CO_2 or other mantle-derived fluids are driving the persistent ES activity at mid-crustal levels at several locations over an area of about 40 km ×60 km (Fig. 1). This geographical region is also characterized by numerous mineral springs, Tertiary–Quaternary volcanism and neotectonic crustal movements, and is located at the intersection of two major intraplate fault zones. It is likely that all these phenomena are related to a common origin.

The area is prone to massive CO_2 degassing that occurs in the form of CO_2-rich mineral waters and wet and dry mofettes in several degassing fields along tectonic fault zones. The gases have high $^3He/^4He$ ratios significantly higher than average continental crust, which is a characteristic indicating their origin deep in the mantle. The long-term degassing of CO_2 in granitic and sedimentary layers makes this area ideally suited to study the effect of CO_2 on the deep biosphere and the development of life at depth.

The ICDP Eger Rift Project aims to develop the most modern, comprehensive observatory worldwide for the study of ES and CO_2 degassing in order to reach a new level of high frequency, near-source, and multi-parameter observation of ES and related phenomena. Such a laboratory will comprise a network of a high frequency 3-D seismic arrays with a set of five to six shallow boreholes. This report summarizes the outcome of the 2nd Eger Rift Workshop held during 4–5 June 2013 in Potsdam, Germany.

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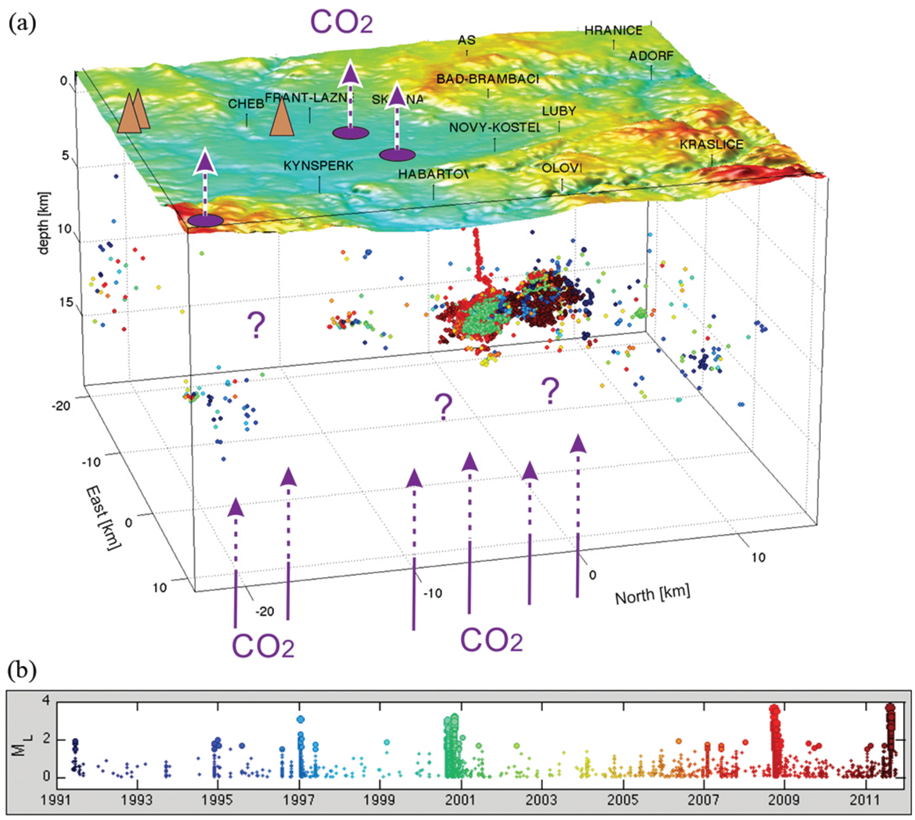

Figure 1. **(a)** Perspective 3-D view of the central earthquake swarm region in West Bohemia–Vogtland. Hypocenters are indicated by filled circles, the magnitudes and time of occurrence is plotted in **(b)** Topography is indicated as coloured map and ranges between 400 and 800 m. Violet arrows sketch the possible CO_2 migration paths (diffuse or in channels). Mofettes indicated by violet ellipses; brown triangles mark known Quaternary volcanoes. See Fig. 3 for location in Central Europe.

2 Earthquake swarms and CO_2 degassing in West Bohemia–Vogtland

Earthquake swarms are usually considered as sequences of numerous small events at shallow depths which cluster in time and space. The few dominant earthquakes do not have similar magnitudes, so smaller events are not associated with any identifiable main shock. This was formerly explained as a consequence of a very heterogeneous stress field and weakened crust, which lacks a single well-developed fault and is incapable of sustaining higher strain (Mogi, 1963). However, nowadays ES are typically interpreted as a consequence of fast fluid movement at depth and the triggering by fluid-induced effective stress. Earthquake swarms often occur in volcanic areas or at geothermal fields (e.g. Dahm and Brandsdottir, 1997; Wyss et al., 1997; Lees, 1998; Dreger et al., 2000; McNutt, 2005). Intraplate earthquake swarms in regions without active volcanism have been reported, for example, at continental rifts like Rio Grande, Kenya, and West Bohemia (Ibs-von Seht et al., 2008).

The first references of earthquake observations in West Bohemia–Vogtland date back to medieval times, however, macroseismically they have been documented since the beginning of the 19th century. Many swarms occurred with the largest equivalent local magnitudes not exceeding M_L 5 (e.g. 1875 or 1908). To date, the largest instrumentally recorded earthquake occurred in the 1985–1986 swarm and reached the magnitude of M_L 4.6 (Vavryčuk, 1993). The seismicity is generally shallow, with the event hypocentres occurring in the upper and middle crust mainly between 5 and 15 km (Fischer and Horálek, 2003).

At present, the highest concentration of earthquake activity and CO_2 degassing occurs in the area of the Cheb Basin, with three Quaternary active volcanoes and the intersection of the Eger Rift and the Regensburg-Leipzig-Rostock Zone (Bankwitz et al., 2003; and Fig. 1). It seems that the earthquake swarms are related to the re-activation of a complex system of faults, at least for the Nový Kostel swarm area. Since 1997, about 80 % of the regional seismic energy has been released beneath Nový Kostel (Fischer and Michálek, 2008). The hypocentres cluster at depths from 6 to 13 km along a steeply dipping fault plane with complicated geometry (Fig. 2). The earthquake swarms show a strongly episodic character and migrating hypocentres with the reactivation of previously ruptured parts on a single fault. Detailed studies of the recent ES at Nový Kostel revealed the

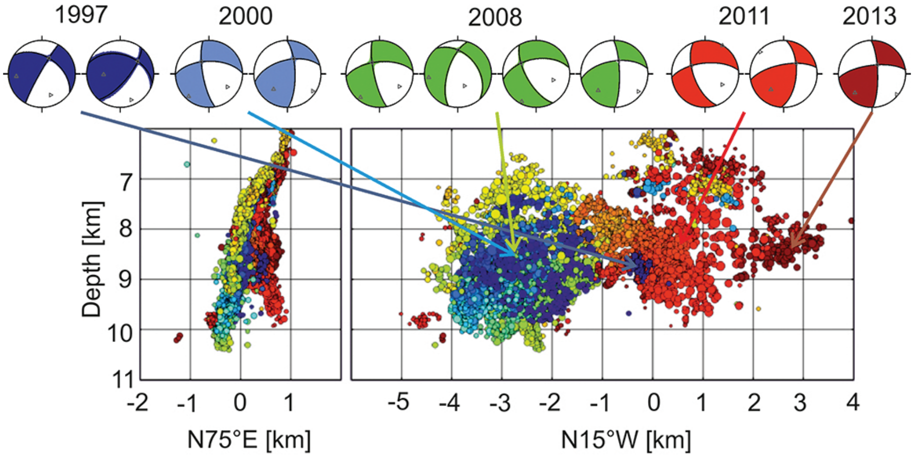

Figure 2. Two perpendicular profile depth sections of the Nový Kostel swarm hypocenters (circles) of swarms 1997 (dark blue), 2000 (blue), 2008 (yellow-green), 2011 (orange-red) and 2013 (dark red). Typical focal solutions are selected for the major swarms. Events are plotted for magnitude larger than 0.5; circle size refers to magnitude. The largest recorded event with magnitude M_L 3.8 occurred in the swarm 2008.

occurrence of clear volumetric and non-double couple source components in the radiation pattern of individual earthquakes (Dahm et al., 2000; Vavryčuk, 2011; Horálek and Šílený, 2013; Vavryčuk et al., 2013). Evidence of volumetric source components is a rare observation worldwide and indicates that faults at depth are under very high fluid overpressure exceeding the minimum principle stress (see also Hainzl et al., 2012; Dahm et al., 2008), which influences the rupture mechanism of micro-earthquakes by means of simultaneous shear-tensile dislocation (e.g. Vavryčuk, 2011). Otherwise, the stress field inverted from the focal mechanisms is consistent with that of Western Europe.

According to carbon isotopic studies, the CO_2 in mineral springs and mofettes of the region originate from the upper mantle (Weinlich et al., 1999; Bräuer et al., 2004). Three degassing centres are supplied by magmatic fluids from magma reservoirs at Moho depths (Bräuer et al., 2008 and Fig. 1). In the Cheb Basin, the portion of mantle-derived helium is the highest and the subcontinental helium isotopic signature indicates fluid transport from the deep lithospheric mantle. The progressive temporal increase in the mantle-helium level may indicate a connection among faults in the deeper crust (Bräuer et al., 2009, 2011). The observed pre-seismic decrease of $^3He/^4He$ ratios, simultaneous increase of the CO_2 emissions and groundwater level changes are interpreted as strain changes in the rocks associated with the preparatory phase of earthquake swarms (Bräuer et al., 2007).

3 Tectonic, volcanic, and structural setting

The Bohemian Massif, one of the largest stable outcrops of pre-Permian rocks in Central and Western Europe, creates the easternmost part of the Variscan orogenic belt and developed approximately between 500 and 250 Ma during a period of large-scale crustal convergence, the collision of continental plates and microplates, and subduction (Matte et al., 1990). West Bohemia is situated in the transition zone among three different Variscan structural units of the Bohemian Massif (Fig. 3). The post-orogenic extension, together with the alkaline magmatic activity during the Cenozoic led to the evolution of the Eger Rift. The Eger Rift is a 300 km long and 50 km wide zone trending ENE–WSW and is an active element of the European Cenozoic Rift System (Prodehl et al., 1995; and Fig. 2). The sedimentary fill of the Cheb Basin consists of Tertiary and Quaternary sediments up to 300 m thick and represents debris of the surrounding magmatic and metamorphic rocks. The tectono-sedimentary structure is associated with a system of Cenozoic sedimentary basins in West Europe and intense intraplate alkaline volcanism (Ulrych et al., 2011). The Quaternary volcanism is documented in at the flanks of the Eger Rift (Proft, 1894; Seifert and Kämpf, 1994; Geissler et al., 2004; Mrlina et al., 2009; and Fig. 1).

The main earthquake swarm area is located at the intersection of two tectonic structures, the ENE–WSW striking Eger Rift and the NNW–SSE striking Mariánské Lázně Fault with the Tertiary Cheb Basin in the centre. The Mariánské Lázně Fault intersects the area close to the main seismo-active zone of Nový Kostel. The position of the Cheb Basin may be controlled by a N–S striking seismo-tectonic structure, the so-called Regensburg-Leipzig-Rostock Zone (Bankwitz et al., 2003).

The crustal and upper mantle structure was previously investigated in several active seismic experiments and passive monitoring (DEKORP Research Group, 1994; Behr et al., 1994; Tomek et al., 1997; Enderle et al., 1998; Hrubcová et al., 2005; Hrubcová and Geissler, 2009; Brűckl et al., 2007; Grad et al., 2008). Passive seismic experiments were carried out to study major lithospheric discontinuities using the receiver function approach (Geissler et al., 2005; Heuer et al.,

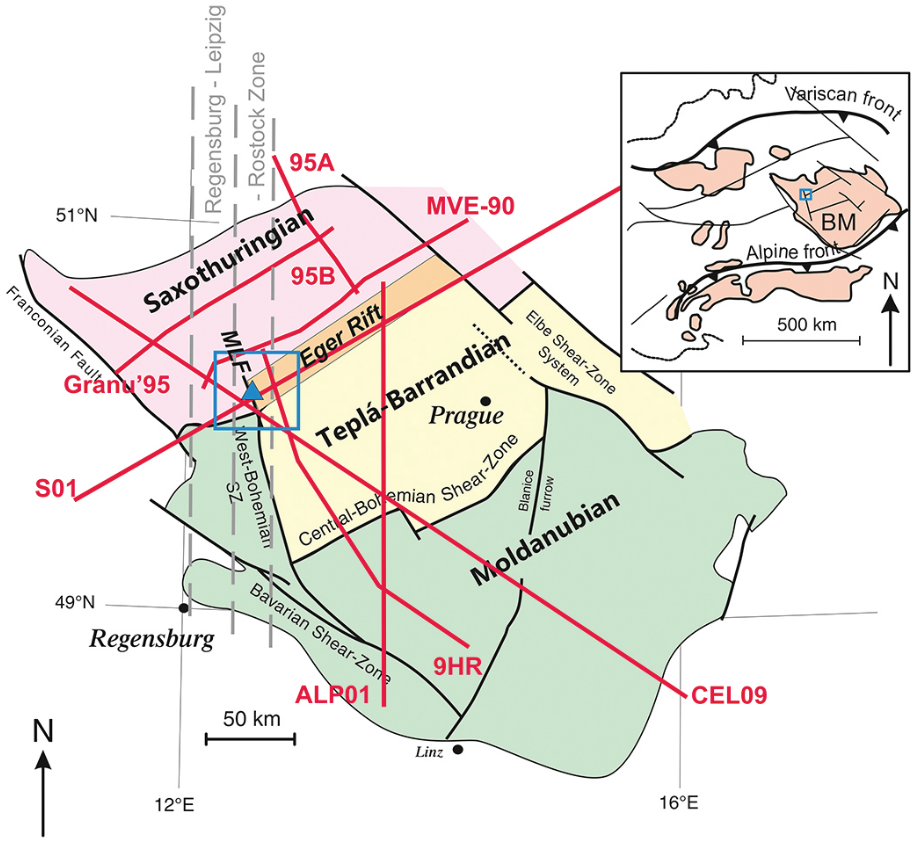

Figure 3. Tectonic-geological setting (after Pitra et al., 1999) indicating major regional tectonic units and shear zones within the Bohemian Massif (BM). The main focal zone at Nový Kostel (see Fig. 1) is indicated by the blue triangle; blue squares refer to area plotted in Fig. 1. Seismic wide angle profiles are indicated by red lines. MLF: Mariánské Lázně Fault.

2006). These investigations exhibited complex crustal structure with a wide zone of increased reflectivity at the crust-mantle transition, confirmed by Hrubcová et al. (2013). According to Geissler et al. (2005), these lower crustal features may be interpreted as low-angle shear zones partly filled with fluids and/or small magmatic intrusions or partial melting as confirmed by mantle xenoliths. Furthermore, recent reprocessing of seismic reflection data revealed an improved structural image of the crust and upper mantle, in particular very distinct and highly reflective features (“bright spots”) in the upper crust which can be directly related to the spatio-temporal behaviour of the swarm activity and their fluid-driven origin (Klemt, 2013; Mullick et al., 2013; Schimschal, 2013).

Geomicrobiology and early life in deep subsurface geo-ecosystems of the Eger Rift

Microbiological studies over the last two decades have shown the existence of diverse and active microbial ecosystems in the deep subsurface (Parkes et al., 2000; Pederson, 2000; Lehman, 2007). Previous studies (Whitman et al., 1998) estimated that between 75 % and 94 % of all microbes on earth occur in deeply buried marine and terrestrial sediments, representing the second-largest pool of living biomass after land plants. Despite recent advances in microbiological deep subsurface exploration, deep terrestrial environments remain relatively unexplored; mainly due to difficulties in obtaining suitable samples. While microbiological research is already part of the “International Ocean Discovery Program” (IODP) (Parkes et al., 1994; D’Hondt et al., 2007) only a few recent projects within the ICDP have had a microbiological component (Colwell et al., 2005; Gohn et al., 2008; Glombitza et al., 2013; Vuillemin and Ariztegui, 2013).

The Eger Rift represents an excellent opportunity to extend our knowledge about microbial life in the terrestrial subsurface. The area hosts a diverse lithology of surficial sediments overlying crystalline rocks as well as active CO_2 degassing and high flow rates of mineral-rich fluids, thereby allowing for the study of many different phenomena. Key research topics would be the development of microbial life in tectonic faults and changes in microbial community composition and metabolic activity in response to changing lithology. It was furthermore hypothesized that deep-reaching tectonic faults in geological active regions like the Eger Rift may provide possible reaction habitats for the formation of prebiotic molecules and the development of early life on the earth (Bräuer et al., 2005; Schreiber et al., 2012).

4 Workshop results

The main goal of the 2nd ICDP Eger Rift Workshop was to discuss a conceptual drilling approach to address the key scientific questions related to the swarm processes. During the meeting, 50 scientists from Germany, Czech Republic, USA, UK, and Poland discussed up-to-date scientific knowledge and plans for drilling in this area during overviews, keynote lectures, and short presentations. Three scientific groups were identified based on their interests in the area: a seismological group, a group interested in tectonics and volcanology/petrology issues, and a paleoclimate/geomicrobiology group. Group discussions concentrated on scientific relevance of the proposed research plans, societal and potential outreach issues, specific requirements for drilling, expected results, and collaborations among groups within the international context, as well as potential funding.

The workshop participants discussed possibilities of deep drilling together with a network of shallow boreholes. They concluded that a better understanding of the earthquake swarm processes and fluid interactions are the key problems. Since a deep drilling cannot reach the seismogenic zone, such problems can be addressed by the planned observatory. This will include questions about whether the earthquakes are fluid driven, the relation of fluids to near-surface mineral water resources, and potential seismic and volcanic hazards in the spa area. Another line of relevance concerns the sustainability of mineral water and hot springs resources, or better quantification of the geothermal potential. The planned observatory will bring a third dimension into the investigation that will improve our knowledge of source parameters, weak earthquakes detection and fluid driven mechanisms. The boreholes will also improve fluid mobility monitoring due to filtration of CO_2 meteorological effects and biosphere monitoring of deep subsurface geo-ecosystems of early life on the earth.

These questions can be addressed by taking a step up from the current short-period seismic monitoring network to a high frequency 3-D seismic array. A set of five to six shallow boreholes (~ 500 m deep) should be equipped with vertical seismic arrays and combined with surface small-aperture high frequency arrays. Such a configuration will allow the study of source and rupturing processes up to 100 Hz and down to the magnitudes of -2. The boreholes of this novel array of 3-D arrays can additionally be used to close azimuthal and take-off angle gaps in the current monitoring network, to include high precision deformation measurements from boreholes (tilt- and strainmeters), to set up a deep monitoring of CO_2 degassing free of the effect of surface environmental parameter variations and allow for heat flow measurements and self-potential monitoring. Reflection seismic-site characterization works around these boreholes as well as such that target the main fault plane of the swarms are mandatory in that respect in order to relate the phenomena observed in the boreholes to the large-scale structure and process of fluid flow in the crust.

These plans will lead to studies of mid-crustal and shallow fluid-rock interaction, the physical and chemical processes for the earthquake swarms, the associated seismic and volcanic hazard, as well as the intra-continental CO_2 flux and fluid transfer through the complete crustal layer. Drilling and coring as well as observations will additionally serve to study the nature of the deep biosphere, petrologic processes, and paleoclimatic issues connected with the massive CO_2 degassing and the existence of Tertiary and Quaternary volcanoes within shallow basin structures.

The workshop resulted in a plan to address the above mentioned issues through 5–6 boreholes approximately 500 m deep in a distance up to 15 or 20 km from the main Nový Kostel seismic zone. Two of the boreholes will be located in Vogtland, four in West Bohemia. The precise sites for drilling will be selected with regards to the results of a new high-resolution reflection seismic profile crossing the Nový Kostel fault zone. Sites in the sedimentary successions of the Cheb Basin will be selected at places that also cover documented CO_2 degassing along a nearby fault zone, as required for gas/chemical and tectonic/petrologic investigations. Boreholes in sedimentary structures will be utilized for volcanological and paleoclimate research while microbiological investigations will centre around sampling of fault structures affected by long-lasting degassing and where microbes most likely have developed during the past.

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Up to now, Scientific Drilling was produced and published by the IODP Management International through the Tokyo office. Due to the current major reorganization of IODP, it is unfortunately not possible for IODP to continue publishing Scientific Drilling.

There was, however, a strong wish from the scientific drilling community to continue Scientific Drilling. The ICDP office in Potsdam, Germany, took over the responsibility for the journal and teamed up with Copernicus Publications as publishing partner to continue Scientific Drilling as an open access journal. Beginning with volume 16, manuscript submission and handling will be operated through a new Scientific Drilling website. Due to financial support from ICDP publication will be free of fees for authors. Past and upcoming volumes of SD can be downloaded from the new Scientific Drilling website and will also be available on ICDP and IODP websites.

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Thomas Wiersberg
(on behalf of the Editorial Board)

The launching of the International Ocean Discovery Program

Drilling expeditions and experiments during the past international ocean drilling programmes (the Deep Sea Drilling Program – DSDP in 1968-1983, the Ocean Drilling Program – ODP in 1983–2003 and the Integrated Ocean Drilling Program – IODP in 2003–2013) have transformed the understanding of our planet by addressing some of the most fundamental questions about Earth’s dynamic history, processes and structure, and by opening up new lines of inquiry. Equally important, scientific ocean drilling has fostered enduring international collaborations, trained new generations of multidisciplinary students and scientists, and engaged the public worldwide in scientific discovery.

Between 2010 and 2012, the twenty five IODP international partners have designed a management structure and business model for future operations that retain both the multiplatform capabilities and the transformative science goals outlined in the Science Plan for the new International Ocean Discovery Program: “Illuminating the Earth’s Past, Present and Future”. This Science Plan is designed to guide multidisciplinary, international collaboration in scientific ocean drilling during the period 2013 to 2023, and highlights four main themes, each encompassing a short list of high-priority scientific challenges:

- Climate and Ocean Change: Reading the Past and Informing the Future;
- Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems;
- Earth Connections: Deep Processes and Their Impact on Earth’s Surface Environment;
- Earth in Motion: Processes and Hazards on Human Time Scales

These themes incorporate shared interests with other national and international research programmes (e.g. the International Continental Scientific Drilling Program, ocean-observing initiatives, Past Global Changes, InterRidge, InterMARGINS).

The International Ocean Discovery Program will have a simplified funding model that will provide better value-for-money than the current IODP. Its architecture will maintain an overarching international umbrella and an international scientific evaluation system, but will allocate more funding flexibility and more independence to the three current Platform Providers: The National Science Foundation (NSF), the Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) and the European Consortium for Ocean Drilling Research (ECORD), which will operate respectively the multipurpose drillship JOIDES Resolution, the riser-drilling-capable Chikyu, and Mission-Specific Platforms (MSP).

Gilbert Camoin

Schedules

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

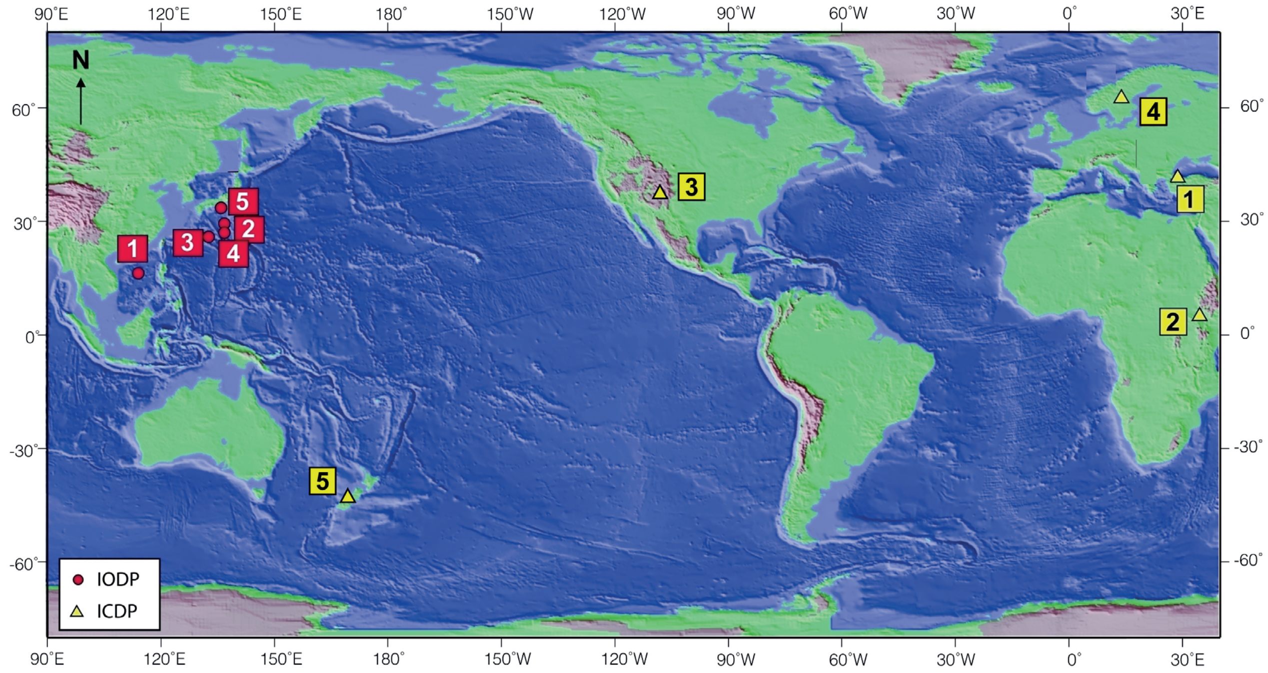
USIO Operations	Platform	Dates	Port of Origin
1 349 South China Sea Tectonics	JOIDES Resolution	26 Jan–30 Mar 2014	Manila, Philippines
2 350 Izu Bonin Mariana Reararc	JOIDES Resolution	30 Mar–30 May 2014	Okinawa, Japan
3 351 Izu Bonin Mariana Arc Origins	JOIDES Resolution	30 May–30 Jul 2014	Yokohama, Japan
4 352 Izu Bonin Mariana Forearc	JOIDES Resolution	30 Jul–29 Sep 2014	Yokohama, Japan

CDEX Operations	Platform	Dates	Port of Origin
5 348 NanTroSEIZE Plate Boundary Deep Riser	Chikyu	13 Sep 2013–20 Jan 2014	Shimizu, Japan

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

ICDP Project	Drilling Dates	Location
1 GONAF	since Sep 2012	Istanbul, Turkey
2 HSPDP	Jun 2013–Mar 2014	Kenya, Ethiopia
3 Colorado Plateau	Nov–Dec 2013	Arizona, USA
4 COSC	Apr–Sep 2014	Jämtland, Sweden
5 Alpine Fault	Sep–Nov 2014	South Island, New Zealand

Locations



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