ISSN 1816-8957

No. 19, May 2015

Scientific Drilling

Reports on Deep Earth Sampling and Monitoring

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

Editorial preface

Dear Reader,

The disastrous M 7.8 earthquake in Nepal on 25 April 2015 drew public attention again to the vulnerability of mankind and infrastructure. And it raised several questions about WHY and HOW scientific drilling can substantially contribute to understanding those uncontrollable and yet unpredictable plate forces acting for example in continental collisional processes such as in the Himalayas.

Although the Nepal earthquake was generated below drillable depths, analogs to Himalayan orogeny can be studied at much shallower depth. Drilling 2.5 km deep into exhumed thrust sheets of the Paleozoic Caledonian orogeny in western Scandinavia (p. 1) provides an ideal site to investigate the deep roots of mountain building. The nappe structures under investigation must have been part of a deep subduction complex before being transported over several hundreds of kilometers.

Near-the-surface subduction processes cause giant earthquakes such as the Great Tohoku earthquake on the Pacific Coast of Japan in 2011. The tsunamigenic slip across and along the Japan Trench has been discussed in a workshop (p. 27) and serves as the stage for future ocean drilling missions to better understand why and how such a large slip occurs.

The Oligocene – Miocene time interval represents a phase of Earth's history after the development of Antarctic ice sheets but before large-scale glaciation in the Northern Hemisphere. Our view on the early evolution of glacial climates and ecosystems in the Northern Hemisphere is restricted due to scarce and incomplete marine records. A workshop brought together specialists from various fields to develop a drilling proposal to fill this gap (p. 39).

Climatic states were even more extreme further back in time. During the Neoproterozoic, ice sheets extending to the tropics for millions of years were followed by ultra-greenhouses. The Neoproterozoic Era played a critical role in the evolution of multi-cellular organisms, and the need for scientific drilling to accelerate Neoproterozoic research was underpinned in a workshop (p. 17).

Little is known not only on the evolution of life in time, but also about the distribution and extension of life on land with depth. How deep can we trace bacteria, archaea or viruses? And what are the limiting factors and nutrients? A meeting report (p. 43) describes how the community will focus in future the research in these fields.

Scientific drilling projects can produce a huge quantity of drill cores. Modern non-destructive drill core investigation techniques provide valuable data in a minimum of time without the need for time-consuming sample preparation or operator intervention. A new and innovative X-ray fluorescence spectrometer is described in a technical report (p. 13).

As a main source of precious metals, such as platinum, the Bushveld Complex in South Africa is a famous giant intrusion; however, interestingly little is known about its true extension, solidification and separation processes, and its role as an early Earth large igneous province. Since most of the exploration is limited to the ore-bearing zones a drilling program has been discussed (p. 33).

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 Engineering Developments, Technical Developments, Workshops, Progress Reports, and news and updates from the community.

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ISSN 1816-8957 • eISSN 1816-3459

Publisher

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

editorial@copernicus.org
production@copernicus.org

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Cover figures: The drill rig of the Greatship Manisha during transit of the IODP Baltic Sea Paleoenvironment Expedition (C. Slomp © ECORD/IODP), Cores stored onboard the Greatship Manisha during the IODP Baltic Sea Paleoenvironment Expedition (D. Smith © ECORD/IODP), COSC Sampling Party at the BGR Core repository in Spanday, Germany (T. Wiersberg © ICDP)

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www.sci-dril.net/19/1/2015/
doi:10.5194/sd-19-1-2015

Scientific Drilling
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Science Reports

COSC-1 – drilling of a subduction-related allochthon in the Palaeozoic Caledonide orogen of Scandinavia

H. Lorenz[1], J.-E. Rosberg[2], C. Juhlin[1], L. Bjelm[2], B. S. G. Almqvist[1], T. Berthet[1], R. Conze[3], D. G. Gee[1], I. Klonowska[1], C. Pascal[4], K. Pedersen[5], N. M. W. Roberts[6], and C.-F. Tsang[1,7]

[1]Department of Earth Sciences, Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden
[2]Engineering Geology, Lund University, John Ericssons väg 1, 221 00 Lund, Sweden
[3]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[4]Institute of Geology, Mineralogy and Geophysics, Ruhr-University Bochum, Universitätsstraße 150, 44780 Bochum, Germany
[5]Department of Civil and Environmental Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[6]NERC Isotope Geosciences Laboratory, British Geological Survey, Nottingham, NG12 5GG, UK
[7]Lawrence Berkely National Laboratory, Earth Sciences Division, 1 Cyclotron Road, MS74R316C, Berkeley, CA 94720, USA

Correspondence to: H. Lorenz (henning.lorenz@geo.uu.se)

Received: 13 February 2015 – Revised: 24 April 2015 – Accepted: 5 May 2015 – Published: 29 May 2015

Abstract. The Collisional Orogeny in the Scandinavian Caledonides (COSC) scientific drilling project focuses on mountain building processes in a major mid-Palaeozoic orogen in western Scandinavia and its comparison with modern analogues. The project investigates the subduction-generated Seve Nape Complex. These in part under ultra-high-pressure conditions metamorphosed outer continental margin and continent–ocean transition zone assemblages were emplaced onto the Baltoscandian platform and there influenced the underlying allochthons and the basement. COSC-1 is the first of two ca. 2.5 km deep, fully cored drill holes located in the vicinity of the abandoned Fröå mine, close to the town of Åre in Jämtland, central Sweden. It sampled a thick section of the lower part of the Seve Complex and was planned to penetrate its basal thrust zone into the underlying lower-grade metamorphosed allochthon. The drill hole reached a depth of 2495.8 m and nearly 100 % core recovery was achieved. Although planning was based on existing geological mapping and new high-resolution seismic surveys, the drilling resulted in some surprises: the Lower Seve Nappe proved to be composed of rather homogenous gneisses, with only subordinate mafic bodies, and its basal thrust zone was unexpectedly thick (> 800 m). The drill hole did not penetrate the bottom of the thrust zone. However, lower-grade metasedimentary rocks were encountered in the lowermost part of the drill hole together with garnetiferous mylonites tens of metres thick. The tectonostratigraphic position is still unclear, and geological and geophysical interpretations are under revision. The compact gneisses host only eight fluid conducting zones of limited transmissivity between 300 m and total depth. Downhole measurements suggest an uncorrected average geothermal gradient of $\sim 20\,^{\circ}\mathrm{C\,km^{-1}}$. This paper summarizes the operations and preliminary results from COSC-1 (ICDP 5054-1-A), drilled from early May to late August 2014, and is complemented by a detailed operational report and the data repository.

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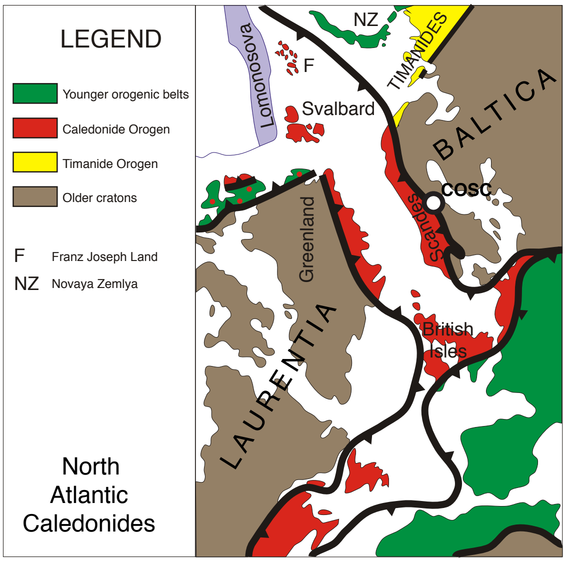

Figure 1. The Caledonides prior to opening of the North Atlantic Ocean. Modified from Lorenz et al. (2012).

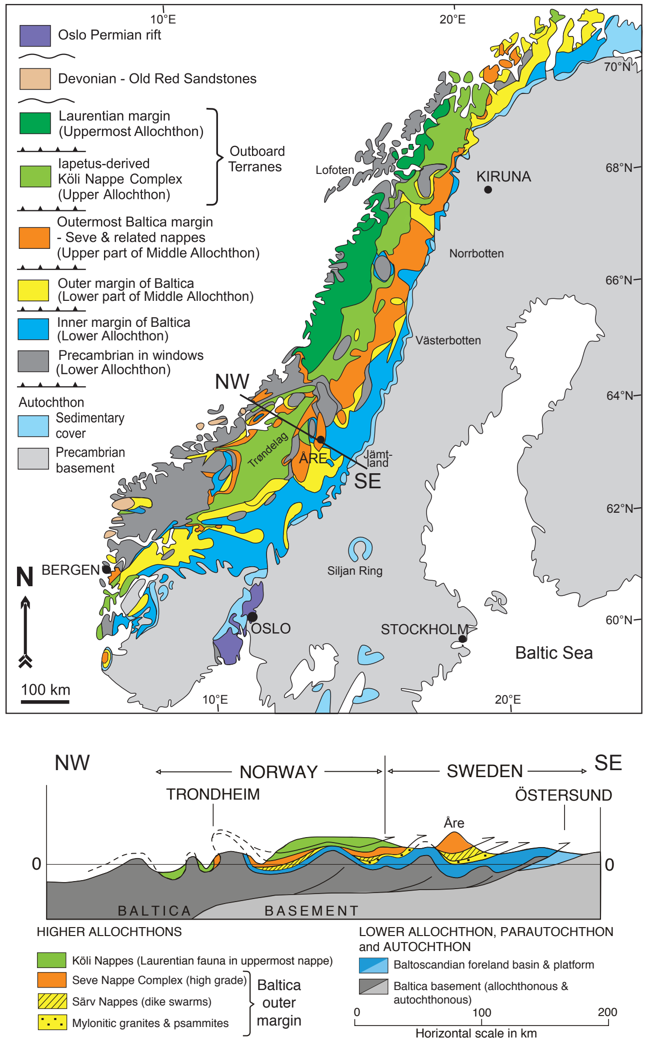

Figure 2. Tectonostratigraphic map of the Scandinavian Caledonides and sketch section along the geotraverse from Östersund to the Norwegian coast. Modified from Gee et al. (2010).

1 The Caledonides – the world's major mid-Palaeozoic mountain belt

The Caledonides of western Scandinavia and eastern Greenland (Fig. 1) have long been recognized to have been part of a collisional orogen of Alpine–Himalayan dimensions, essentially the result of the closure of the Iapetus Ocean during the Ordovician and subsequent underthrusting of continent Laurentia by Baltica in the Silurian and Early Devonian during Scandian collisional orogeny. Several hundreds of kilometres of thrust emplacement of allochthons have been demonstrated, E-directed in the Scandes and W-directed in Greenland. In both the Scandinavian and Greenland Caledonides, the allochthons that originated from the outer parts of the continental margins were subjected to high-grade metamorphism and emplaced, apparently hot, onto the adjacent platforms (cf. Gee et al., 2008). Baltica, as the smaller of the two palaeo-continents involved in the collision (referred to as Scandian orogeny in the North Atlantic region), played a similar role to that of India in the present-day Himalaya–Tibet context. The Scandinavian Caledonides comprise thrust sheets transported onto the Palaeozoic platform successions of the Baltoscandian margin of Baltica (Fig. 2). The Caledonian front is marked by a sole thrust that dips 1–2° westwards beneath the orogen, underlain by a thin veneer of Cambrian (locally Ediacaran) sedimentary rocks that unconformably overlie Proterozoic crystalline basement. The thrust sheets are subdivided into the Lower, Middle, Upper and Uppermost allochthons (Gee et al., 1985). The Lower Allochthon (Jämtlandian Nappes) is dominated by a sedimentary succession of Neoproterozoic and Cambro-Silurian strata, featuring westerly-derived turbidites in the Ordovician and Silurian. Only minor basement-derived units are incorporated in eastern parts of this allochthon (Greiling et al., 1998), but towards the west, seismic profiling suggests that the basal decollement passes beneath the crystalline basement exposed in windows (Palm et al., 1991; Juhojuntti et al., 2001). The Middle Allochthon is of higher metamorphic grade than the underlying units (Andréasson and Gorbatschev, 1980). In most areas it contains a basal basement-derived thrust sheet (e.g. the Tännes Augen Gneiss Nappe), overlain by greenschist facies Offerdal Nappe metasandstones, composing the footwall for the remarkable Särv Nappe (Strömberg, 1961) with its abundant ca. 600 Ma dolerite dyke swarms. The sedimentary host rocks are composed of Neoproterozoic sandstones with subordinate carbonates and tillites (Kumpulainen, 1980). The uppermost tectonic unit in the Middle Allochthon (Andréasson and Gee, 2008; Gee et al., 2008), previously included in the Upper Allochthon, is the Seve Nappe Complex, composed in most areas of three units (Sjöström, 1983; van Roermund, 1985; Bergman and Sjöström, 1997): a lower part of similar protolith to the Särv Nappe, but ductilely deformed in amphibolite (locally eclogite) facies; a central part (e.g. Åreskutan Nappe) of migmatites and paragneisses (Arnbom, 1980) with a previous ultra-high-pressure metamorphic history (Klonowska et al., 2015); and an upper, amphibolite-dominated unit with micaschists and psammites. The high-grade metamorphism and leucogranite intrusions of the Seve Nappes have yielded Early Silurian ages (Gromet et al., 1996; Williams and Claesson, 1987; Ladenberger et al., 2014). The entire Middle Allochthon was derived from west of the Norwegian coast and the upper units transported at least 400 km eastwards during Scandian orogeny (Gee, 1978). The tectonostratigraphically highest rocks in Jämtland are the Köli Nappes in the Upper Allochthon. This low to high greenschist facies unit contains basal slices of ophiolite (e.g. at Handöl) and is dominated by sedimentary rocks of Early Palaeozoic age (Kulling, 1933). The Uppermost Allochthon, metasedimentary and carbonate rocks inferred to be derived from the Laurentian margin are only exposed farther to the northwest in the mountain belt.

2 Scientific objectives

The COSC project aims to study mountain building processes at mid-crustal levels in a major orogen, in particular the transport and emplacement of subduction-related high-grade allochthons with a focus on the Seve Nappe Complex. During the last 4 years of preparation for the drilling, following the initial COSC workshop in 2010 (Lorenz et al., 2011), investigations of the Seve Nappe Complex in the Jämtland area have improved our understanding of the subduction systems that existed along the Baltoscandian margin during Ordovician closure of the Iapetus Ocean. Ultra-high-pressure metamorphism was recognized in both the lower and middle parts of the Seve Nappe Complex in northern Jämtland (Janák et al., 2013) and the Middle Ordovician age confirmed (Root and Corfu, 2012). In central Jämtland, both in the Åreskutan Nappe and 50 km farther west in the correlative Snashögarna Nappe (Majka et al., 2014; Klonowska et al., 2015), microdiamonds were discovered in garnets of the "granulite facies" migmatitic gneisses. These discoveries have profound implications for our understanding of Caledonian orogeny in Scandinavia and for the interpretation of high-grade rocks in the orogen, particularly those in the deeper structural levels of the hinterland (e.g. in the Western Gneiss Region of southern Norway) where basement and allochthonous cover were subducted a second time in the Early Devonian, during the final phases of Scandian collision.

Topical working groups developed the scientific objectives of the COSC scientific drilling project. Major targets are the following:

- to establish a coherent model of mid-Palaeozoic (Scandian) mountain building and to apply these new insights to the interpretation of modern analogues, in particular the Himalaya–Tibet mountain belt;
- to determine the origin of observed seismic reflections and constrain geophysical interpretations in order to use this information to further our understanding of the geological structure of the mountain belt and the Fennoscandian basement;
- to refine knowledge on climate change at high latitudes, including historical global changes, recent palaeoclimate development (since last ice age);
- to understand the hydrological characteristics of the geological units and research present groundwater circulation patterns of the mountain belt;
- to analyse the extent, functions and diversity of microorganisms in the drill hole as a function of the different penetrated geological strata and their depth.

3 Strategy

Two wireline fully cored drill holes, each to ca. 2.5 km depth, can penetrate through the tectonic stack from the high-grade Lower Seve Nappe and well into the Baltican basement. COSC-1, near Åre, was finished during 2014 (this paper) and has a focus on the Middle Allochthon with its inverted metamorphic gradient, thick ductile shear zones and mylonites (Fig. 3). At the top of the mountain Åreskutan, ultra-high-pressure gneisses of the Åreskutan Nappe are exposed (Klonowska et al., 2015). These rocks can be followed downwards, along the slopes of Åreskutan into the underlying, amphibolite facies gneisses of the Lower Seve Nappe. There, the COSC-1 borehole is located and provides a nearly complete section through the Lower Seve Nappe and into the underlying thrust zone. COSC-2 will begin drilling in units of similar tectonostratigraphic position as those encountered in the deepest parts of COSC-1. Thus, its geographical location will be farther east towards the thrust front. COSC-2 will investigate the composition, metamorphism and structure of the Lower Allochthon, the basal decollement, footwall alum shale and underlying Precambrian basement (Fig. 3).

4 Technical operations

This paper is complemented by the COSC-1 operational report with detailed explanations at doi:10.2312/ICDP.2015.002 (Lorenz et al., 2015a).

Table 1. Location of the boreholes on the COSC-1 drill site obtained by differential GPS, geodetic datum WGS84 (EPSG:4326).

Name	Designation	Driller's depth (m)	Latitude	Longitude	Elevation (m a.s.l.)
COSC-1	5054-1-A	2495.8	63.401629° N	013.202926° E	522.8
Observation 1	5054-1-B	100	63.401788° N	013.202924° E	522.5
Observation 2	5054-1-C	50	63.401762° N	013.202819° E	522.5

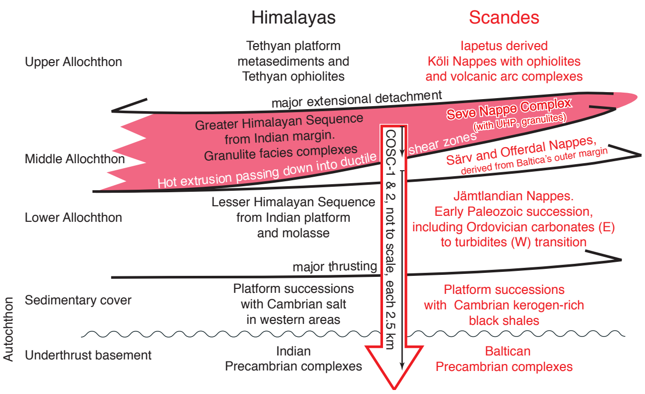

Figure 3. Schematic comparison of tectonostratigraphic units between Himalayas and Scandes with COSC-1 and COSC-2 indicated.

To determine the optimal location for the COSC-1 drill site (Fig. 4), a high-resolution reflection seismic survey was carried out in 2010 and extended in 2011. Details on the 2010 survey can be found in Hedin et al. (2012). The scientific criterion for the selection of the drill site was to sample an as-thick-as-possible section of the Lower Seve Nappe before penetrating through the thrust zone and into the underlying nappes. Technical criteria were accessibility, infrastructure and a good relationship with the land owner, Åre municipality.

The drill site occupies an area of approximately 1050 m^2 (30 m × 35 m, Fig. 5) and is constructed of compacted soil material covered by angular rocks separated with a geotextile as barrier. A circular cellar construction was built by placing two concrete rings, inner diameter 1.2 m, around the position for the planned COSC-1 borehole (5054-1-A). Initially a 3 m long surface casing with an outer diameter (OD) of 193.8 mm and an inner diameter (ID) of 183.8 mm was installed. Thereafter a hole with 165 mm diameter was drilled down to 103 m using a 5-inch down-the-hole (DTH) hammer and the conductor casing (OD 139.7 mm/ID 129.7 mm) installed and cemented from the bottom to the surface.

Two additional drill holes to 100 m (5054-1-B) and 50 m (5054-1-C), respectively, were drilled, equipped with seismometers and cemented for passive monitoring of the drilling operations. The exact locations of all drill holes are given in Table 1.

Drilling operations started on 1 May 2014 and were completed on 26 August 2014. Drilling operations were conducted 24 h day^{-1} with initially two drillers per 12 h shift and three drillers below 545 m depth (after 2 weeks of drilling). The total depth (TD) of COSC-1 is 2495.8 m.

Drilling was conducted with the Swedish national research infrastructure for scientific drilling ("Riksriggen") at Lund University, Sweden. The well head included a 5″ annular blow out preventer (BOP; Fig. 6), and the mud tanks had a volume of ca. 20 m^3. The drill rig (Fig. 7) can handle the three common sizes P, H and N (123/85 mm, 96/63 mm and 76/48 mm hole/core diameter) with depth capacities of around 1050, 1600 and 2500 m, respectively. Three core barrel assemblies were deployed (inner tube sample length, core diameter, hole diameter):

– H-size triple tube (3 m/61 mm/96 mm);

– N-size triple tube (3 m/45 mm/75.7 mm);

– N-size double tube (6 m/47.6 mm/75.7 mm).

A double-tube core barrel assembly consists of an outer tube (drill string) with an inner tube (core barrel) that captures the core sample. The triple tube has an additional split tube ("core liner") placed inside of the inner tube for protection of the drill core. The inner tube is equipped with a spearhead and release mechanism at the top for retrieval and with a core lifter at the bottom. The drill bit and reamers are attached to the outer tube.

For HQ3 core drilling (103–1616 m), light-weight drill rods with reinforced threads (HRQ V-wall) were employed together with diamond-impregnated drill bits and surface set reamers. Below 770 m, a so-called rod reamer was attached between the core barrel assembly and the drill rods. The drilling fluid down to 500 m was fresh water. From 500 to 1616 m a bio-degradable polymer was added to reduce the friction between the drill string and the borehole walls and to improve the removal of cuttings. After HQ3 drilling was completed, the HRQ-drill string was installed as temporary casing from surface down to 1616 m: the casing/drill string was not cemented to allow for removal after drilling was finished. Drilling continued with an N-size triple-tube core barrel assembly (NQ3, 1616–1709 m and drill rods (NRQ V-wall) and bits comparable to those used during H-size drilling. A standard reamer was placed above the drill bit and a surface set adapter coupling replaced the standard adapter coupling above the core barrel assembly. Below 1709 m, a double-tube core barrel assembly (NQ) was deployed, which increased the sample length from 3 to 6 m for each core run in

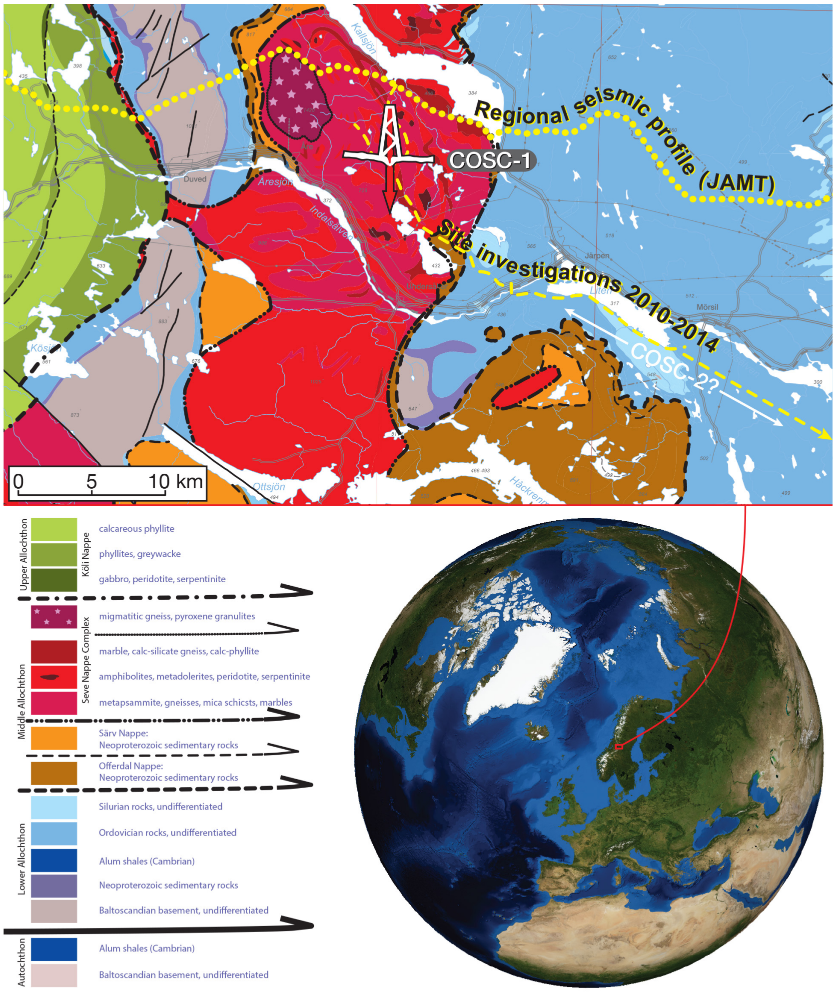

Figure 4. Tectonostratigraphic map of the Åre-Järpen area (based on the 1 : 200 000 scale geological map by the Geological Survey of Sweden). The map shows the COSC-1 drill site and relevant geophysical surveys in relationship to the tectonic units of the Scandinavian Caledonides.

order to save time (30–40 % faster). At 1965 m, the NRQ V-wall drill string was replaced with standard NRQ drill rods. Below 2000 m a second polymer was added to the mud to reduce friction.

After reaching TD the NRQ-drill string was placed on the bottom of the hole and disconnected at the surface. Thereafter the HRQ-drill string (the temporary casing) was successfully retrieved and the mud column replaced with fresh water through the NRQ-drill string. An end of hole deviation survey was conducted while the NRQ-drill string was pulled out of the hole. The drill hole has very small deviation (Fig. 8). It is only cased down to 103 m and below left as an open-hole completion. Despite a major problem with deformed drill rods and resulting problems with friction in the borehole, the target depth was reached – however, with a considerable delay because of slower penetration rates and more frequent round trips to replace the quickly worn-out drill bit. Unfortunately, dedicated triple-tube drilling for microbial samples had to be omitted because of the switch to faster double-tube drilling.

5 Scientific operations

The on-site scientific work was performed in two 12 h shifts per day. Normally, three scientists were on site at any time during the operational phase. The complete on-site scientific work from mobilization to demobilization is estimated to about 4.75 man-years. The core-handling procedure by the on-site science team (Fig. 9) was conducted under rigorous control of top and bottom, and the resulting data sets are detailed below. On-site sampling of the drill core was very restricted and only permitted for the studies of thermal conductivity in relation to time after drilling (sample to be returned), matrix gas extraction and analysis (samples have been returned), and microbiology (destructive). All samples in the COSC scientific drilling project are marked with an Inter-

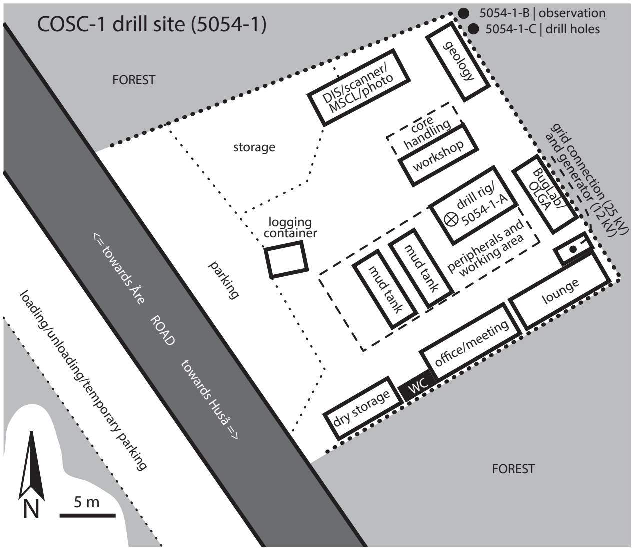

Figure 5. Sketch of the COSC-1 drill site. The working area of the drill site is nearly quadratic with an area of about 1050 m^2. The drill rig, the combined mud tanks and manual pipe handling system and some peripherals such as workshop and mud mixer formed the central part of the drill site. In immediate proximity to the northwest, the BugLab container (Mangelsdorf and Kallmeyer, 2010) was located. It hosted OLGA, the online gas monitoring system (Erzinger et al., 2006; Wiersberg and Erzinger, 2011), and provided space for microbiological work and mud sampling. The southeastern part of the drill site was occupied by common facilities and office space. In the northern quarter of the drill site, the on-site science was located. The remaining space was used as storage space for drill rods, logging equipment, and drill core and for parking.

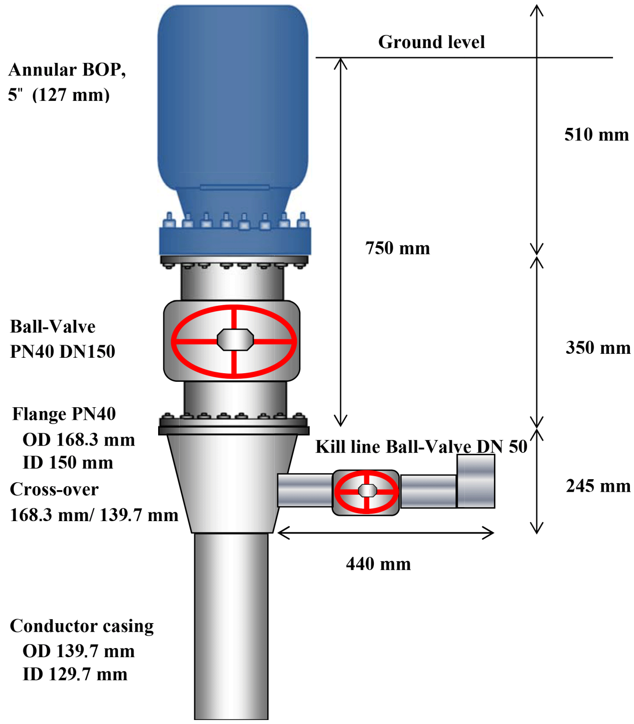

Figure 6. Sketch of the COSC-1 wellhead. A 5″ annular blow out preventer (BOP) was attached on top of the main valve, a DN150 ball valve. A DN50 ball valve was used for the kill line.

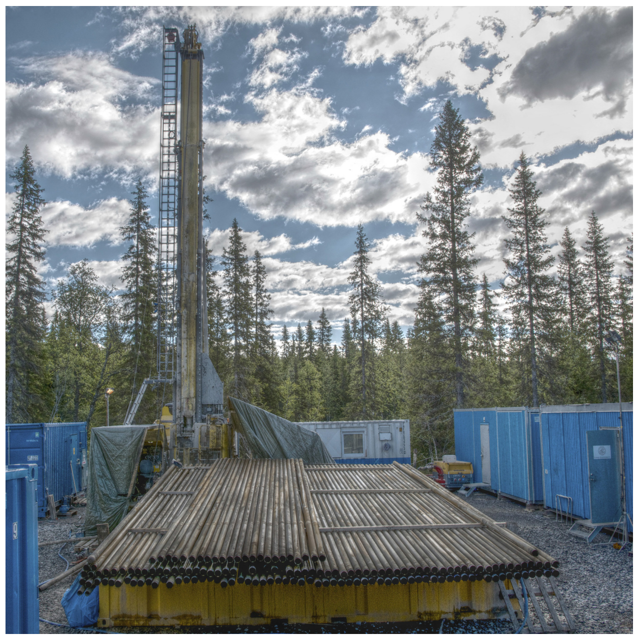

Figure 7. The Swedish national research infrastructure for scientific drilling, "Riksriggen". An Atlas Copco CT20C crawler mounted drill rig with a manual pipe handling system mounted on top of the mud tanks, with ca. 1400 m of HRQ drill pipe in this photograph.

national GeoSample Number (IGSN), a hierarchical unique identifier that is used to track samples and relationships between samples (see also www.geosamples.org/igsnabout).

Due to the relative simplicity of the mud composition, mud logging was restricted to pH, temperature and conductivity measurements every 4 h. Samples were taken every 8 h and are archived together with the drill core. The On-Line GAs monitoring system (OLGA; Erzinger et al., 2006) was for the first time deployed to qualitatively analyse mud gasses in a slim hole and diamond core drilling project. Despite the substantially different parameters when compared to oil-field-type drilling, in which the system had successfully been employed before (Wiersberg and Erzinger, 2011), this experiment was a success.

Several logging campaigns were performed during drilling breaks to secure data in case of a hole loss while drilling and complemented by a comprehensive post-drilling downhole logging programme. Unfortunately, not all instruments were available due to technical problems. A major post-drilling seismic survey was carried out in and around the COSC-1 drill hole, including vertical seismic profiling (VSP) in the drill hole, a sparse 3-D survey centred on the drill hole and three long-offset profiles centred on the drill hole equipped

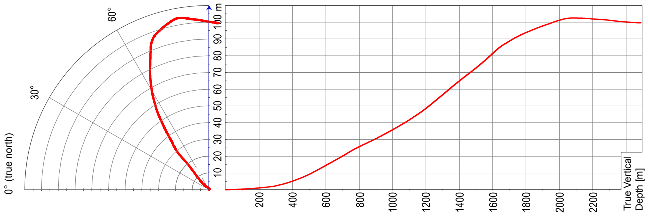

Figure 8. The COSC-1 drill hole deviation, seen from above (with azimuth) and plotted vs. depth: 10 × horizontal exaggeration.

with 15 3C geophones. The data from this survey will be published elsewhere.

6 Drill core

According to the scientific documentation, 2396.0 m of the drill core was recovered, resulting in a core recovery of 100.12 %. The content of two inner tubes was lost in the drill hole because of malfunctioning core catchers and had to be "over-drilled" in order to retrieve it. In total, approx. 2.5 m of the drill core was unaccounted for (i.e. documented core loss).

Down to about 1800 m, the COSC-1 drill hole penetrated a succession that is dominated by gneisses of varying compositions (felsic, amphibole, calc–silicate, other), often garnet and diopside bearing. Metagabbros and amphibolites are common and apparently correlate with seismic reflections between 500 and 1000 m depth. Also marbles, pegmatite dykes and minor mylonites occur. These rocks are highly strained. Small-scale structures (e.g. isoclinal folding) are occasionally discernible in the narrow section provided by the drill cores. (Young) Fractures are sparse. One obviously fluid-conducting set of very steep fractures results in dissolution of calcite-rich bands in the gneisses to form "micro-karst" (at about 175 m and several levels between 1200 and 1320 m).

First signs of increasing strain appear shortly below 1700 m in the form of narrow deformation bands and thin mylonites. The mylonites increase in thickness to around 1 m between 1900 and 2000 m. Below ca. 2100 m, mylonites dominate and garnets become common (but are not present in all mylonites). The deepest rock of mafic origin, possibly an amphibolite in the Seve Nappe, was identified at 2314 m. A transition from gneiss into lower-grade metasedimentary rocks occurs between 2345 and 2360 m. The lower part of the drill core to TD is dominated by quartzites and metasandstones of unclear tectonostratigraphic position that are mylonitized to a varying degree. The rocks sampled in the lowermost part of the drill core are the thickest mylonites encountered, tens of metres thick and (again) rich in garnet.

The COSC-1 drill core is archived at the Core Repository for Scientific Drilling at the Federal Institute for Geosciences and Natural Resources (BGR), Wilhelmstr. 25–30, 13593 Berlin (Spandau), Germany. The first sampling party was held from 2 to 6 February 2015 at the core repository, where samples that amount to ca. 110 m total length were taken for laboratory investigations.

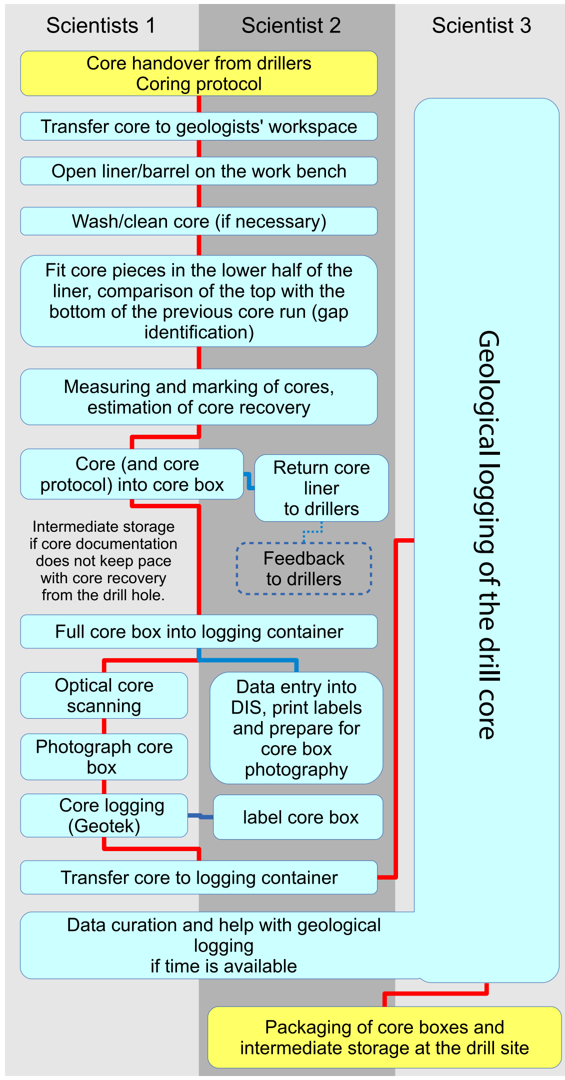

Figure 9. Flowchart over the COSC-1 drill core processing workflow.

7 Basic data

The COSC-1 basic data with detailed documentation are available at doi:10.1594/GFZ.SDDB.ICDP.5054.2015 (Lorenz et al., 2015b) and include the following:

- technical data acquired at the drill rig;
- drill core metadata including the number of core run, depth, length of core run, sections, length of sections, core recovery, core orientation (where applicable) and the location of sections in core boxes;

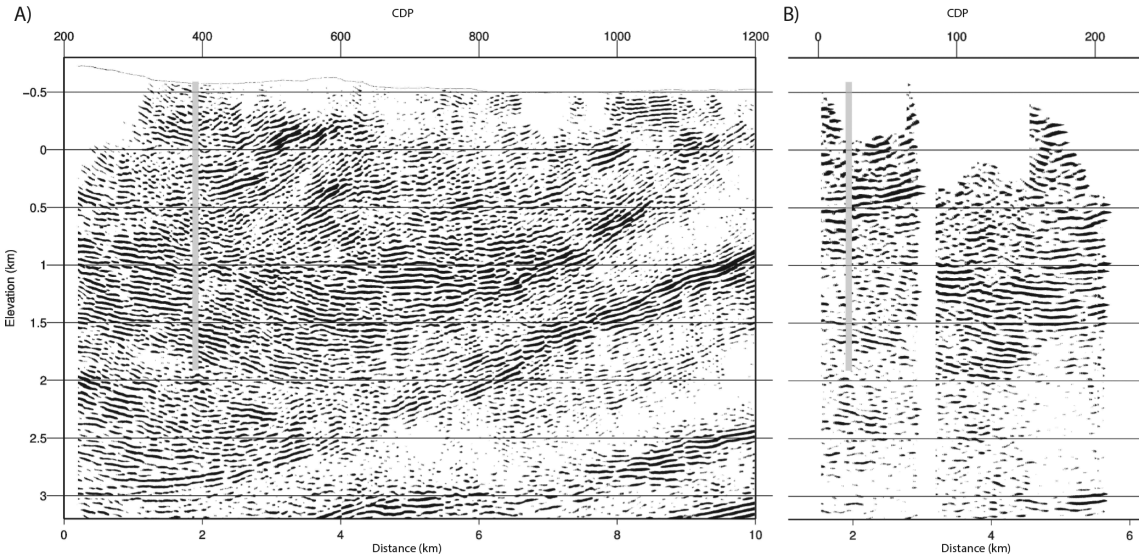

Figure 10. Seismic data from the pre-drilling seismic survey **(a)** as in Hedin et al. (2012) **(b)** reprocessed with a 3-D geometry over the crooked acquisition line. The grey vertical line indicates the location of the COSC-1 drill hole.

– the geological description of the drill core;

– unrolled core scans;

– core box images;

– geophysical parameters of the drill core: density, P wave velocity and magnetic susceptibility; the sensors of the MSCL were calibrated every day, but problems were observed (please refer to the full operational report);

– XRF geochemical data. For details refer to Sjöqvist et al. (2015);

– mud parameters;

– mud gas analyses (OLGA) for a nearly complete depth profile was compiled for the interval from 662 to 2490 m depth;

– downhole logging data from Lund University and ICDP OSG.

8 Preliminary scientific assessment

The COSC-1 drill core provides a complete and unique geological section through the lower part of the Lower Seve Nappe and into the underlying thrust zone. The geological description of the drill core while drilling was difficult, with rotating personnel and field expertise that is not readily applicable to the drill core. Thus, the geological description of the drill core will be revised, based on the XRF survey and dedicated geochemical and mineralogical investigations. In anticipation of detailed investigations by the COSC science team, a couple of direct observations concerning the geology can be made. The gneisses of the Lower Seve Nappe are more homogenous than expected, in principle similar from the surface to > 2000 m, amphibolite gneisses, felsic gneisses, calc–silicate gneisses dominating at different levels. A major surprise is the thickness of the thrust zone at the bottom of the Seve Nappe. About 800 m below the first shear bands and mylonites, its lower boundary was not reached. However, high-grade gneisses had passed into metasandstones, indicating that the drill hole had either entered an underlying unit or a tectonic sliver of it. Close to the bottom of the drill hole, mylonites in metasandstones contain a large proportion of garnet of considerable size (occasionally up to 1 cm). This suggests metamorphic conditions that support garnet growth in the deformation zones late during thrusting.

The integrated interpretation of the geophysical and geological data before drilling was to a large extent confirmed, with the exception of the lower part of the drill hole. Two-dimensional crooked line processing of the pre-drilling seismic survey over the COSC-1 site (Hedin et al., 2012) showed a highly reflective unit to be present from the near surface down to about 2.2 km (Fig. 10a). Correlation of this reflective unit, and the less reflective rock below it, to the boundary between the Seve Nappe Complex and the Ordovician turbidites about 9 km to the east of the COSC-1 site suggested that the high reflectivity was a characteristic of the Seve Nappe Complex itself. Later sparse 3-D processing of the crooked line data indicated significant lateral variability in the reflectivity. At the location of the COSC-1 borehole it appeared that the rock was most reflective in the uppermost 1 km with a rather distinct reflection originating at about 900 m depth (Fig. 10b). A gently east-dipping reflec-

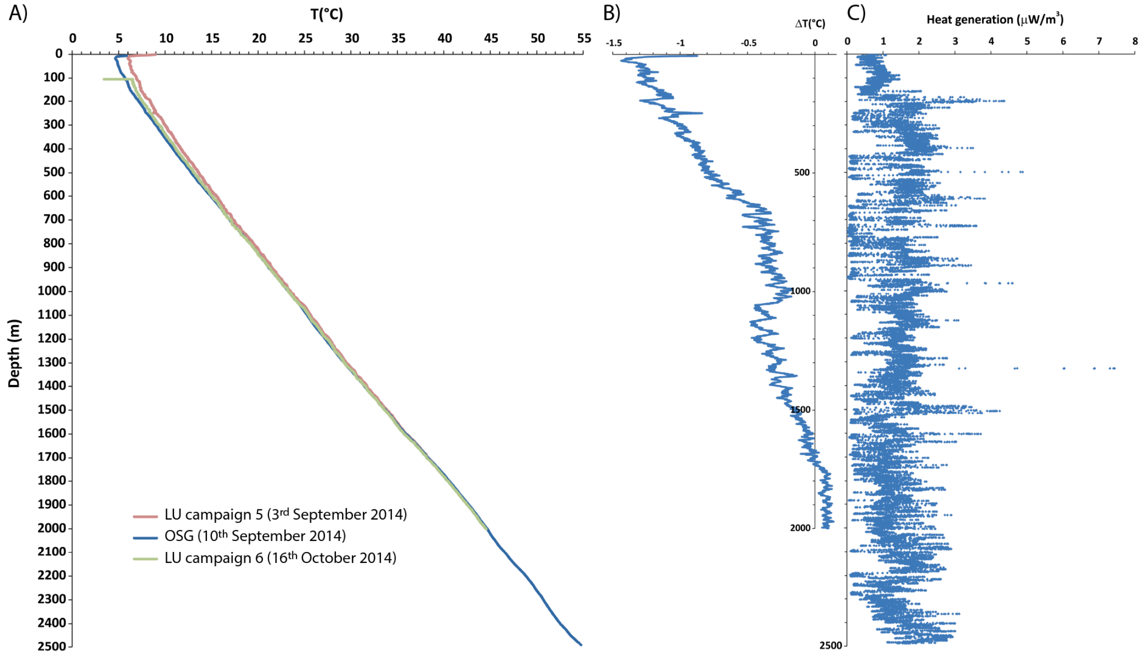

Figure 11. **(a)** Post-drilling temperature logs. Note gradual cooling (i.e. thermal re-equilibration) of the uppermost section of the borehole early in September 2014. The log measured in October is affected by post-drilling operations. **(b)** Temperature variations (ΔT) in the COSC-1 drill hole from 3 until 10 September 2014. **(c)** Heat generation rates as derived from the spectral gamma log measured in the COSC-1 drill hole.

tion coming from about 2.1 km depth was thought to represent the base of the Seve Nappe Complex. The uppermost 500 m was poorly imaged due to the acquisition geometry. Potential field modelling (Hedin et al., 2014) also indicated the base of the Seve Nappe Complex to be at about 2 km depth at the COSC-1 site, consistent with the seismic data.

Preliminary analyses of the geophysical logging data and the geophysical core parameters show that the upper 1000 m contain the largest proportion of thicker amphibolite units (> 15 m). The interval 1000 to 1800 m also contains a significant proportion of amphibolite, but the units are generally much thinner than above 1000 m. Below 1800 m, amphibolites are much less common. It is likely that it is the contrast in velocity and density between amphibolite and gneiss that is generating much of the reflectivity within the Seve Nappe Complex. Given that the average velocity of the complex is 6000 m s^{-1} and that the dominant frequency in the surface seismic data is 70–80 Hz, the layers which are on the order of 20 m thick will generate the strongest reflections due to tuning. This is consistent with observations on the 3-D sparse processed data, which indicate the upper 1000 m to have higher-amplitude reflections in the COSC-1 area (Fig. 10b). The extensive post-drilling seismic survey will help to better define the geometry of the base of the Seve Nappe Complex in the vicinity of the COSC-1 borehole. The combined use of surface and borehole seismics will provide true 3-D coverage around the borehole and allow better resolution imaging at depth.

In a pre-drilling survey in 2012, the temperature of 18 abandoned mining boreholes was logged down to 100–200 m. The temperature gradients were expectedly low and constrained the average ground temperatures to ~ 4 °C at elevations corresponding to the COSC-1 drill site (~ 500 m a.s.l.). Six temperature logs and one spectral gamma log were acquired after drilling was finished. However, three of the temperature logs were measured only 4 days after a pumping test, and other post-drilling operations were conducted in the hole. These logs show signs of temperature disturbances (Fig. 11a). A fourth temperature log acquired between 1600 m and TD shows a surprising offset with respect to all other measured temperature profiles. Only two temperature logs recorded respectively 6 and 13 days after final cleaning of the drill hole can give some insights on the expected steady state (Fig. 11a). The relatively slow temperature recovery observed between ~ 1600 and 2000 m depth (Fig. 11b) suggests negligible deviations from true formation temperatures along this specific depth interval and an uncorrected average gradient of ~ 20 °C km^{-1}. A preliminary estimation of heat generation rates based on the spectral gamma log indicates moderate heat production in the penetrated rocks (Fig. 11c). The sharp spikes in the heat generation profile are mostly related to highly radioactive pegmatite dykes. Future temperature measurements in the COSC-1 drill hole will include the installation of a 2.5 km distributed temperature sensing optical fibre in 2015. Thermal property measurements were conducted up to four times on 24 core samples coming from 5 different depth ranges using a thermal conductivity scanning device. Thermal and hydraulic properties are planned to be measured on 100 core samples. Ten representative samples will be shared for laboratory comparisons.

Hydrogeological tests were conducted during a drilling break at 1616 m and at TD. COSC-1 provided the opportunity to introduce a hydraulic test with negligible impact on the drilling schedule and the potential to provide important and accurate information on in situ hydraulic conductivities on both high- and low-transmissivity zones already during the drilling period. The particular testing method used was the flowing fluid electric conductivity (FFEC) logging method, which is capable of identifying large and small hydraulically active zones and provides data that can be used to estimate their transmissivity values and local formation water salinity (Tsang et al., 1990; Tsang and Doughty, 2003; Doughty et al., 2013). Based on FFEC logging, eight hydraulically active zones between 300 m and TD were identified. Transmissivity values are very low and range over 1 order of magnitude.

Due to technical problems and strategic decisions, deep biosphere research was restricted to drill core samples taken directly after opening of the inner tube. ATP and DNA swab samples were taken where the on-site science team encountered open fractures in the drill core. These samples are successively being processed and analysed. However, the complete equipment necessary for dedicated core drilling for microbiological research was adopted to "Riksriggen" and tested during the drilling operations and, thus, can easily be deployed in future projects.

9 Conclusions

The drilling of COSC-1 was very successful and provided the scientific community with nearly complete and unique sample material from a high-grade metamorphic nappe and its basal thrust zone, and with access to a largely uncased drill hole. Questions that originate from the COSC-1 drilling are the nature and tectonostratigraphic position of the seemingly lower-grade metamorphic rocks close to the bottom of the drill hole and how they relate to the intercalated garnetiferous mylonites. Did the garnet grow before and/or during deformation? What is the protolith of the mylonites?

COSC-1 research will continue during the coming years. In the meantime, the planning for COSC-2 has already begun: to drill through the basal Caledonian detachment into the basement of the Fennoscandian Shield.

Acknowledgements. COSC-1 was financed by the International Continental Scientific Drilling Program (ICDP) and the Swedish Research Council (VR – Grant 2013-94).

The Geological Survey of Sweden (SGU) supported the project with data acquisition over the target area during the planning phase and with in-kind contributions during the operational phase. In R & D collaborations, Devico AS supplied a core orientation tool for NQ drilling and borehole orientation data, and Minalyze AB scanned the whole drill core with their new XRF scanner (cf. Sjöqvist et al., 2015). The ICDP Operational Support Group (OSG) provided training and practical help.

This project would never have been possible without the help of all the volunteers, who did a great job. Many thanks to the drilling team for a superb drill hole and core to almost 2500 m despite technical problems and the sometimes seemingly endless succession of nights and days with pipe handling. A full list of personnel is available in the operational report at doi:10.2312/ICDP.2015.002.

Edited by: T. Wiersberg
Reviewed by: A. Lepland and two anonymous referees

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Sci. Dril., 19, 13–16, 2015
www.sci-dril.net/19/13/2015/
doi:10.5194/sd-19-13-2015

Scientific Drilling
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An innovative optical and chemical drill core scanner

A. S. L. Sjöqvist[1], M. Arthursson[1], A. Lundström[1], E. Calderón Estrada[1], A. Inerfeldt[1], and H. Lorenz[2]

[1]Minalyze AB, Industrivägen 4, 433 61 Sävedalen, Sweden
[2]Department of Earth Sciences, Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden

Correspondence to: A. S. L. Sjöqvist (axel.sjoqvist@minalyze.com)

Received: 16 February 2015 – Revised: 9 April 2015 – Accepted: 13 April 2015 – Published: 29 May 2015

Abstract. We describe a new innovative drill core scanner that semi-automatedly analyses drill cores directly in drill core trays with X-ray fluorescence spectrometry, without the need for much sample preparation or operator intervention. The instrument is fed with entire core trays, which are photographed at high resolution and scanned by a 3-D profiling laser. Algorithms recognise the geometry of the core tray, number of slots, location of the drill cores, calculate the optimal scanning path, and execute a continuous XRF analysis of 2 cm width along the core. The instrument is equipped with critical analytical components that allow an effective QA/QC routine to be implemented. It is a mobile instrument that can be manoeuvred by a single person with a manual pallet jack.

1 Introduction

Rapid decision-making and a continuous re-evaluation are the key to successful commercial and scientific drilling projects. Geochemical information of drill cores is important base information for many projects and crucial for certain applications, like exploration and mining drilling. A major drawback is that performing geochemical analyses takes time. Thus, expensive rig time is often spent while waiting for results, and decisions might be made with only incomplete background information at hand. An in-depth analysis of the drilling industry has revealed that access to even rudimentary geochemical information in an early stage after drilling has substantial advantages for the planning and implementation of the subsequent scientific and analytical work.

A concept instrument was envisioned, which would analyse drill cores with a non-destructive methodology and minimal interference with other on-site work in terms of time and labour. Since drill cores are handled in core trays with multiple slots, the processing of whole core trays (compared to individual sections) is an efficient way to analyse great lengths of drill core. The first step was to prove the reliability of using an in situ non-destructive analytical technology on drill core surfaces. The prototype instrument (for 0.5 m long sections) demonstrated with the successful analysis of more than 22 km of drill core that energy-dispersive X-ray spectrometry on drill core surface is a viable approach. After this proof of concept, the construction of the first complete system commenced in October 2013.

2 Instrument specifications and capabilities

The semi-automated new drill core scanner is built with flexibility in mind (Fig. 1). More than anything else, the instrument is a platform that handles drill cores in core trays. The methodology of processing entire drill core trays is patented and thus unique. The composition of the drill core tray does not matter. Exactly which sensors and attachments are coupled to that platform depends on specific project needs and advances in analytical technology. The current set-up is described below and summarised in Table 1.

2.1 Digital photography and 3-D scanning

The high-resolution RGB line scan camera produces digital photo documentation of the drill cores and trays. Digital images are stored in 8 bits per channel lossless TIFF and can have a pixel resolution of up to 10 px mm^{-1}.

For reliable analytical results it is of the highest importance to have accurate information about the location and geometry of the samples. For this purpose a 3-D model of the core tray with its contents is created from a laser scan, performed at the same time as RGB imaging. Algorithms devel-

Published by Copernicus Publications on behalf of the IODP and the ICDP.

Figure 1. The new instrument described is a drill core scanner that intelligently handles entire drill core trays to produce chemical analyses of drill cores.

Table 1. Technical specifications of the new instrument.

Dimensions	1.8 m × 1.3 m × 1.2 m ($L \times W \times H$)
Mass	ca. 1 t
Electrical supply	Three phase 400 V, 16 A
Power consumption	ca. 3 kW
Cooling	External, quick-connect fittings
Photography, line	Up to 10 px mm^{-1}, 8 bit lossless TIFF
3-D profiling, line	1 mm × 0.34 mm × 17 µm ($L \times W \times H$)
Chemical analysis method	ED-XRF
Detection range, in air	(Mg), Al–U
Spatial resolution	Down to 1 mm
Normal throughput	15–20 m h^{-1}

oped by us calculate the geometry of the core tray, the number of slots, the location and geometry of drill core pieces, and the optimal path to scan without colliding the detector, which should be kept at a constant distance to the drill core.

Secondary benefits of having detailed information about the drill core geometry are that the drill core length is measured and cracks are semi-automatically identified, which is useful for geotechnical purposes, e.g. RQD (rock quality designation) and fracture frequency.

2.2 XRF analysis

In situ non-destructive chemical analyses of the drill cores are acquired through X-ray fluorescence (XRF) analysis by energy-dispersive spectrometry (EDS), using a high-quality silicon drift detector (SDD). A partial vacuum between the irradiated sample surface and the detector window protects the sensitive Be detector window from dust contamination and also reduces attenuation by the air in the lower energy range of the X-ray spectrum, thus enabling the detection of elements down to Al or Mg.

X-ray tubes with different anode target materials are available, e.g. Cr, Mo, and Ag. The selection of anode material depends on the project-specific analytical preferences. The X-ray beam is collimated to a linear beam that is 2 cm wide and 1 mm thick perpendicular to the drill core axis.

Table 2. Specifications of the analytical parameters used for scanning the COSC-1 drill core with the new instrument.

X-ray tube anode	Cr
Voltage	40 kV
Current	20 mA
Elemental suite	Al, Si, P, S, Cl, K, Ca, Ti, Fe, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Pb
Scanning speed	10 mm s^{-1}
Analysis resolution	0.1 m

Scanning is performed in a continuous motion, and the data over a certain length are integrated. The scanning speed and integration length depend on the user's requirements for analysis precision and resolution, and the drill core's chemical composition. Confident detection of the typical major and minor elements of interest (cf. Table 2) is usually achieved with a real-time analysis of 10 s. With a typical scanning speed of 1 cm s^{-1} this corresponds to a distance of 10 cm. The analytical parameters, the scanning speed, and the integration length for the analysis need to be evaluated and adjusted for each project. Typical throughput is of the order of two to four drill core trays per hour, depending on the number of slots and the complexity of the scanning path, which for a six-slot drill core tray means an effective scanning throughput of approximately 15–20 m h^{-1}.

The instrument is a stand-alone system. No additional external processing or storage capabilities are required. Chemical analyses are processed in real time and can be displayed on the screen while scanning.

The X-ray beam location and intensity are monitored throughout the scanning process and logged to monitor instrument drift. Two sample holders for pressed pellets or glass pucks allow easy analytical calibration and detector drift measurements with matrix-matched certified reference materials, or analyses of blank samples. This provides easy access to critical components for performing effective QA/QC (quality assurance/quality control) routines during an analytical campaign.

2.3 Operation, connectivity, mobility, and safety

The entire instrument runs off a single three-phase plug (400 V, 16 A) and consumes approximately 3 kW. In remote areas, a diesel generator can deliver enough power. Use of a back-up uninterruptible power supply (UPS) is recommended to ensure operation stability. The instrument is conveniently operated by the resistive touch screen, which can be used with any type of safety gloves.

Front-end connectivity includes a 230 V socket, USB ports, and an Ethernet port. The user can connect devices that are most convenient for the moment, whether it is a USB hard disk, mouse and keyboard, Wi-Fi antenna, or 4G mobile Internet dongle.

The bottom plate hosts furrows that allow the instrument to be lifted and moved around by a forklift truck or manual pallet jack by one person. The total mass of the system is approximately 1 t.

For the sake of flexibility, the X-ray tube water-cooling system is external and connected to the instrument by quick-connect fittings. One could choose to locate the cooling system in another room or, in hot climates, to upgrade to a larger system.

The radiation-blocking protective shell consists of two layers of 3 mm thick steel, and the window is made of lead glass. The instrument has all necessary radiation safety requirements and is completely safe to work with.

3 Geoscientific applications

Rock drill cores are the most tangible representations of unexposed subsurface geology. However, drilling is expensive and the amount of sample very limited. Multiple investigations on the drill core require that the number of destructive analyses is limited to the absolutely necessary. A quick and non-destructive method for obtaining geochemical information, like XRF scanning, is therefore an asset. The instrument, with its combination of digital photography, 3-D profiling, and chemical analyses, effectively creates a digital representation of the drill core, which then can be evaluated in its undisturbed original form in a virtual drill core archive.

Availability of chemical information early in the process of drill core processing greatly facilitates the geological documentation, making drill core logging more objective and less dependent on the individual geologist's experience and best judgement. This is of particular importance for subsequent and advanced studies that utilise the base scientific documentation of a project.

While researchers have performed tests to analyse unprepared rock drill cores by XRF for a long time (Carlsson and Akselsson, 1981), in recent years unprepared rock drill cores have almost exclusively been analysed by portable/handheld XRF instruments. Portable/handheld XRF instruments are gaining popularity and have been applied widely and successfully to analyse drill cores in a non-destructive way (e.g. Gazley et al., 2011, 2012; Fisher et al., 2014; Le Vaillant et al., 2014; Ross et al., 2014). Advantages of the new instrument over handheld XRF instruments are a better and more representative coverage (continuous scanning vs. point analyses), reduced labour, standardised analytical conditions, integrated routines, and advanced data handling.

4 Preliminary high-resolution chemical data from COSC-1

During October–November of 2014, the entire COSC-1 drill core (Collisional Orogeny in the Scandinavian Caledonides ICDP; cf. Lorenz et al., 2015) was scanned with the new

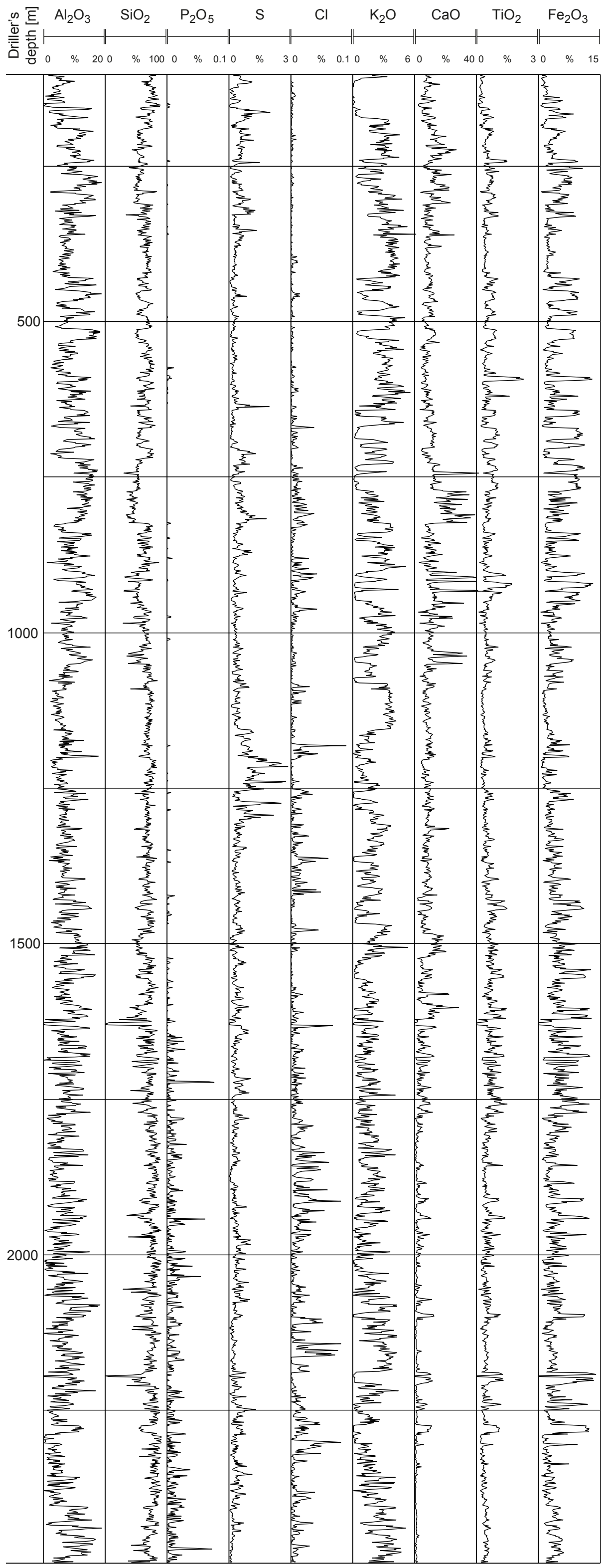

Figure 2. Preliminary chemical data of major elements produced by the new instrument of the full length of the COSC-1 drill core, scanned with 0.1 m resolution.

instrument described here. The ca. 2400 m of drill core, whereof ca. 1500 m in *H* size (76 mm diameter) and 900 m in *N* size (47.8 and 45 mm), are boxed in 719 core trays with four slots for HQ and five compartments for NQ. The analytical parameters are described in Table 2. A preliminary assessment of the analytical precision yields an estimated precision for major elements better than 5–10 % and better than 20 % for most trace elements.

The COSC-1 drill core consists of mainly high-grade metamorphosed siliceous sedimentary rocks. Felsic, calc-silicate, and amphibole gneisses are typical representatives, with marbles, amphibolites, and subordinate porphyries. The lower part of the core is dominated by the mylonites of a major thrust zone. A first assessment of the preliminary XRF data (Fig. 2) shows an increase in SiO_2 with depth and that elevated levels of Cl and P_2O_5 occur in the thrust zone, possibly introduced by fluids. High CaO content and associated elevated Sr levels in the upper and middle part of the drill core can be linked to marbles and possibly calc-silicate gneisses, which become less frequent in the lower part. Peaks in the density, *P* wave velocity, and rock resistivity downhole logs seem to correlate with low SiO_2 values of amphibolites. A more detailed assessment of the data produced by the new instrument started with the utilisation XRF data during the COSC-1 sampling party in Berlin, 2–6 February 2015, where they helped the scientists to select their sampling spots.

5 Summary

A new instrument provides fast, non-destructive chemical analyses of drill cores in drill core trays by automated scanning XRF. The mobile and autonomous system can be moved and operated anywhere in the world. Drill cores are documented by high-resolution digital photography and 3-D laser profiling. 3-D topographic information is used to calculate the optimal scanning path automatically, and for length and structural measurements of the drill core. The instrument allows scientists to obtain basic chemical data early in a project, e.g. on the drill site where the analyses immediately become available to geologists. Subsequently, core logging is less subjective and less dependent on the individual's experience. Non-destructive XRF analyses leave more of the drill core to be used for other studies. In addition, a digital copy of the drill core can be stored in a virtual drill core archive in which drill cores can be (re)evaluated in their original state.

Acknowledgements. Minalyze wishes to acknowledge B. Arthursson, N. Bragsjö, M. Halonen, E. Hegardt, L. Hellberg, C. Johansson, V. Krpo, V. Kunavuti, A. Nordlund, J. Nordstrand, M. Rostedt, C. Sernevi, A. Smajic, and I. Zagerholm, who have played a role in developing the drill core scanner called Minalyzer CS from concept to functional instrument.

Edited by: U. Harms
Reviewed by: U. Harms and A. Schleicher

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Sci. Dril., 19, 17–25, 2015
www.sci-dril.net/19/17/2015/
doi:10.5194/sd-19-17-2015

Scientific Drilling
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Accelerating Neoproterozoic research through scientific drilling

D. J. Condon[1], P. Boggiani[2], D. Fike[3], G. P. Halverson[4], S. Kasemann[5], A. H. Knoll[6], F. A. Macdonald[6], A. R. Prave[7], and M. Zhu[8]

[1]NERC Isotope Geoscience Facilities, British Geological Survey, Nottingham, UK
[2]Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil
[3]Department of Earth & Planetary Sciences, Washington University, Washington, USA
[4]Department of Earth & Planetary Sciences, McGill University, Montreal, Canada
[5]Department of Geosciences, University of Bremen, Bremen, Germany
[6]Department of Earth & Planetary Sciences, Harvard University, Cambridge, USA
[7]Department of Earth & Environmental Sciences, University of St Andrews, St Andrews, UK
[8]State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China

Correspondence to: D. J. Condon (dcondon@bgs.ac.uk)

Received: 28 September 2014 – Revised: 20 January 2015 – Accepted: 21 January 2015 – Published: 29 May 2015

1 Introduction

The Neoproterozoic Era (1000–541 Ma) and early Cambrian Period (541 to ∼520 Ma) record Earth system changes unlike any other in Earth history (Fig. 1). The start of the Neoproterozoic witnessed the merger of the supercontinent Rodinia, followed by its breakup and dispersal into fragments that form the core of today's continents (Dalziel, 1997; Hoffman, 1991; Li et al., 2008). Climatic states were extreme, with ice sheets extending to the tropics for millions of years followed by ultra-greenhouses; these snowball Earth episodes occurred at least twice (Hoffman, 2009). These tectonic and climatic events occurred in concert with pivotal reorganisations of major biogeochemical cycles potentially accompanied by a rise in oxygen (termed the Neoproterozoic Oxygenation Event, or NOE), and the diversification of eukaryotes followed by the rise of animals (e.g. Erwin et al., 2011; Och and Shields-Zhou, 2012; Fig. 1). Such a concentration of hallmark events in the evolution of our planet is unparalleled. The study of the inter-relations between these events define the forefront of interdisciplinary research between climatology, palaeobiology, geochemistry, geochronology and other fields of geology, yet many outstanding questions remain to be answered (see Sect. 2).

In September 2012 an international conference on the Neoproterozoic Era (evolution, glaciation and oxygenation) (Rose, 2013) served as the catalyst that initiated discussions to define future strategies to enable Neoproterozoic-focussed research; at the end of this meeting a discussion session was dedicated to this topic and outlining future research priorities. One proposition was to develop a scientific drilling programme for advancing Neoproterozoic research. Subsequently, joint workshop proposals were submitted to the ICDP and the ECORD Magellan+ schemes, resulting in the 2014 workshop at the British Geological Survey, UK, with 44 Earth scientists in attendance from 14 countries. The collective conclusion was the desired ambition to achieve for the Neoproterozoic what the IODP is accomplishing for the Cenozoic: an extensive core archive and associated generation of new, high-quality geochemical, stratigraphic, palaeomagnetic, palaeontological, and geochronological data to address robustly the exciting questions emerging regarding the conditions that transitioned Earth from the Proterozoic into the Phanerozoic. It was also discussed how to use this programme as a catalyst, a transformative mechanism for instigating a network of collaboration through open-access data archiving and information infrastructure development to be populated by the findings of a multidisciplinary, worldwide alliance of Neoproterozoic researchers. Finally, the nature and magnitude of effort involved in scientific drilling means that it often serves as a catalyst for enhanced collaboration

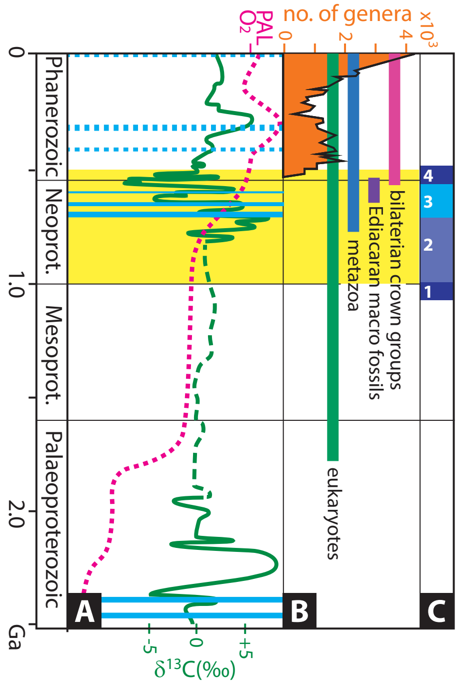

Figure 1. Timeline from the base of the Palaeoproterozoic to present showing the context of the Neoproterozoic to Cambrian rock record targeted for the proposed drilling programme (highlighted in the yellow band). **(a)** Generalised $\delta^{13}C$ and O_2 (relative to present atmospheric level (PAL)) and major ice age periods shown as horizontal blue bands (solid band signifies global-scale glaciation, dashed band indicates high-latitude glaciation; **(b)** major evolutionary events; and **(c)** tectonic events related to the Neoproterozoic–Cambrian time slice (1 – Grenville orogeny; 2 – Rodinia Supercontinent; 3 – Rodinia break-up and drift phase; 4 – Pan-African orogeny). See Halverson et al. (2005), Och and Shields-Zhou (2012), and references therein for data sources.

which then has a positive feedback into the science being done.

The main objectives of the workshop were to

- bring key researchers from a range of countries, and representing a full range of specialities, together to discuss and plan collaboration for advancing research on the Neoproterozoic Era;
- discuss, broker and prioritise key target localities and stratigraphic intervals, and to prioritise strategies for formulating drilling proposals;
- discuss and plan a community-guided, data-management and -archiving environment;
- discuss science themes, organise scientific teams and outline leaders’ and members’ responsibilities;
- discuss potential sources and models of financial support.

Unlike most other ICDP and ECORD workshop topics, this one was not centred on a single site or collection of sites in one area. Instead it was agreed that the remit of this initiative had to be ambitious: the questions are global in nature hence the drilling strategy had to be commensurate with addressing the questions regarding the time interval spanning ∼ 1000 to 520 Ma for key successions located on a number of cratons. This ambition of multi-craton coverage for a ∼ 500 Myr time interval is a multi-decade endeavour that will only be realised through numerous coordinated, collaborative projects centred on both core and outcrop archives. In addition to the specific drilling projects, the issues relating to developing and sustaining an overarching initiative were topics for discussion.

2 Outstanding research questions and problems

Although advances have been made in the past 2 decades in documenting and interpreting Neoproterozoic events, significant gaps remain: the exact timing of many of the key events is unknown, their durations remain poorly constrained, and techniques for interpreting physical conditions during these events range from satisfying to speculative. Also, it is poorly known how geographically disparate records (Fig. 2) relate to one another in a 4-D framework: are records that are considered related, and therefore correlative, actually synchronous? Combined, these shortcomings create a healthy tension between how existing observations from the rock record inform on the predictions of biospheric and environmental models (both conceptual and numerical) and the data now needed to verify or reject them.

2.1 Cryogenian inception

A first-order question is why did the Earth system transition from the relatively climatically stable Mesoproterozoic to an interval of extreme climate and environmental change? A set of relatively stable conditions persisted during the Mesoproterozoic (the so-called “boring billion”), which was characterised by the apparent lack of major geochemical or climatic events. It is unknown what generated the conditions during the Tonian (∼ 1.0 to 0.75 Ga) that caused a threshold to be crossed and transition into the Cryogenian Period with its severe geochemical and climate fluctuations that framed the origin of animals.

- What were the tectonic and environmental boundary conditions prior to the earliest Cryogenian glaciations? A current favoured hypothesis is that tecono–volcanic-weathering processes produced the atmospheric thresholds that resulted in a low-latitude (Snowball Earth) glaciation (Godderis et al., 2003);
- What was the cause and nature of the ∼ 810 Ma Bitter Springs (negative C-isotopic) stage (see Fig. 2)? This

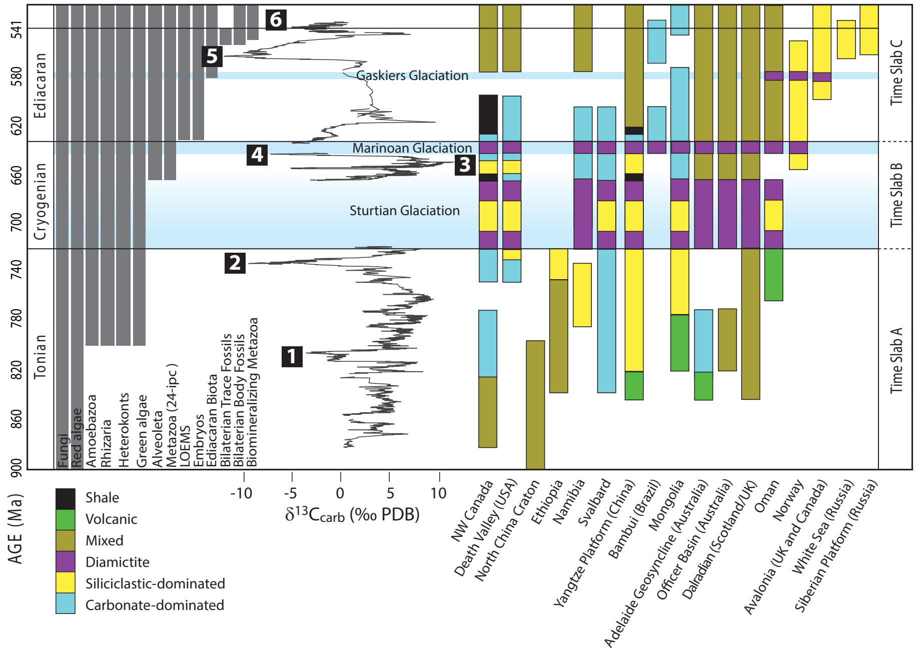

Figure 2. Schematic timeline showing major evolutionary events, a composited δ^{13}C curve with numbered isotope anomalies (1 – Bitter Springs; 2 – Islay; 3 – Keele Peak; 4 – Trezona; 5 – Shuram; 6 – BASE) and an approximation of the stratigraphic distribution and dominant lithology type for a number of key Neoproterozoic successions that occur worldwide. Time slabs identified for drilling are shown on the right.

excursion is not associated with evidence for glaciation yet appears to be a global signal. Some workers attribute this to inertial interchange true polar wander (Maloof et al., 2006).

– What caused the radiation of crown group eukaryotes (fungi, algae, etc.), which appears to coincide with the Bitter Springs stage?

2.2 Timing of environmental perturbations and extreme climate change

Chemostratigraphic studies worldwide reveal patterns and trends in multi-isotopic systems that have been used to construct the first-order "event" framework depicted in Fig. 2: three major glacial epochs and their temporal association with isotope excursions, geochemical proxies for marine oxygenation, and the fossil record. These have been gleaned from integrating mapping, stratigraphic analysis and geochronology (e.g. Condon et al., 2005; Halverson et al., 2005; Macdonald et al., 2010). This chronology of the Neoproterozoic stratigraphic record, though, is constrained by only a few key radioisotopic dating studies (e.g. Bowring et al., 2007; Condon et al., 2005; Kendall et al., 2004; Macdonald et al., 2010; Rooney et al., 2014) and the exact durations and timing of many of the major climatic and biogeochemical episodes remain unresolved. Building beyond this first-order picture requires a higher-resolution temporal calibration so that successions from different regions can be compared, contrasted and integrated with confidence, and rate dependent processes can be quantified and assessed. Questions that require answers include the following:

– Do the geochemical proxy archives record regional and/or global events, and at what level can synchroneity be demonstrated? How are global signals regionally modulated?

– What controlled the timing of glaciations, their durations and the feedbacks that moderated their reoccurrence, as well as what processes formed the contrasting cap carbonates?

– What is the relationship between large carbon isotope anomalies such as the Islay, Taishir, and Trezona anomalies and the onset of glaciation (Fig. 2)?

– What was the genesis and nature of the largest C-cycle isotopic perturbation in Earth history, the Ediacaran-age Shuram–Wonoka excursion (Fig. 2)?

2.3 The advent of animals and impact (feedbacks) on environment

The Earth system houses a suite of interconnected feedback loops and interactions between the coupled biosphere–atmosphere–lithosphere systems that influence and control atmosphere–ocean compositions and the viability of life. A question engaging palaeobiologists and geochemists alike is what changes in the Earth system presaged the origin and early evolution of animals. Along with that question, many others follow.

- What was the common ancestor of metazoans? What were the first animals and when did they evolve?
- What is the interconnectedness, if any, between the repetitive environmental extremes and changes of Cryogenian time and animal evolution?
- How did the evolution of complex life impact on and respond to changes in ocean and atmospheric chemistry?

Although progress has been made in advancing our collective understanding of these topics (e.g. Boyle et al., 2014; Butterfield, 2011; Erwin et al., 2011; Knoll, 2014; Shields-Zhou and Zhu, 2013), these questions remain the subject of much focussed effort and debate, and a rich area for research. Fundamental to understanding the mechanistic relationship between environment and life is establishing an accurate chronology of global change and the temporal calibration of the fossil record.

2.4 Geochemical proxies of environmental conditions and the rise of oxygen

Complementing palaeontological studies, geochemists are detailing systematic patterns in redox sensitive elemental ratios to explore the hypothesis that the advent of animals may have been a consequence of a second global oxygenation event during Ediacaran time, the NOE (e.g. Lyons et al., 2014; Och and Shields-Zhou, 2012; Sahoo et al., 2012).

- Were there Neoproterozoic oxygenation events? And if so, where, when and why?
- What is the relationship(s) between atmospheric oxygen, marine redox, and geochemical proxies, and how do these change over this interval (e.g. associated with the onset of bioturbation)?
- What was the magnitude and tempo of the purported $p\mathrm{O_2}$ rise near the end of Ediacaran time? Neither is known and both need to be established.
- Was the rise in $\mathrm{O_2}$ a response to a unique geological situation in the Neoproterozoic such that the rate of oxygen consumption decreased (a decrease in the magnitude of oxygen sinks) so that oxygen levels rose via the steady-state photosynthetic production of $\mathrm{O_2}$?
- Was the rise in $\mathrm{O_2}$ the trigger for the advent and expansion of animals, or did animals evolve in response to a biological control such that evolutionary chance enabled development of a genetic toolkit for the growth of large organisms?

These are first-order questions that need to be evaluated through a global-scale data set that is substantially more comprehensive than we have at present. Integrated proxy records of biology and environment connected to precise and accurate stratigraphies are needed to interrogate these issues and determine cause-and-effect relationships.

3 Developing underpinning data sets

In addition to the scientific challenges outlined above it was discussed how solving each of these is dependent upon a system of key underpinning data sets.

3.1 Highly resolved chronostratigraphic framework(s)

The outstanding scientific questions/issues articulated above are necessarily global in their nature, however (nearly) all of the proxy records we use to address them are necessarily local. Combining local records to develop regional and then global data sets requires the development of resolved chronostratigraphic records that are developed independent of proxy data such that lags and leads assessed and the rates of environmental change quantified can be objectively assessed. The issue of inter-regional correlation is complicated by the nature of the Neoproterozoic stratigraphic record – much of what is being sampled are epeiric seas and continental margins, and not necessarily the open oceans. Consequently, the likelihood that local archives reflect a modulated expression of a global signal is increased, making it difficult to assess the importance of local records and their use for global correlation (see below). In contrast to Phanerozoic stratigraphy the Neoproterozoic stratigraphic record is constrained by limited number of radioisotopic constraints, a coarse biostratigraphic zonation based upon limited micro- and macrofossils (whose range is often poorly constrained), a nascent data set of radiogenic isotope ($^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$) and an "event stratigraphy" that is based upon an integration of distinct lithologies (e.g. glacial rocks, cap carbonates) integrated with sequence stratigraphy and stable isotope chemostratigraphy (primarily $\delta^{13}\mathrm{C}$). The environmental dependence of geochemical data can be assessed by integrating elemental and isotopic data into an objectively constrained depositional framework. The reliance of "event stratigraphy" for correlation is due to a dearth of radioisotopic constraints, and the possibility of circular reasoning has led to a number of correlation schemes being questioned (Kennedy et al., 1998). Over the past 2 decades predictive tests (i.e. reproducibility) and an increasing number of radioisotopic dates have been able to test and inform the "event"-based correlation leading to an evolving ordering/sequencing of events/records (Fig. 2).

The challenge for future research is to develop and build upon the first-order sequencing that has been established. Whilst radioisotopic dating does support certain key events, such as the end of the Marinoan glaciation being globally synchronous (Calver et al., 2013; Condon et al., 2005; Hoffmann et al., 2004), future efforts must focus on developing geochronological-based frameworks for each of the hallmark biogeochemical and climatic events of Neoproterozoic time, as well for the records of second-order events/processes (e.g. timing and duration of unconformities), and integrating those into a worldwide temporally constrained geological framework. Only with such a framework of objectively interlinked geochronology, chemostratigraphy, palaeobiology and geology will the underpinning data become relatable enough to determine timing and rates of processes and events and, hence, enable solid scientific tests of climatic, biospheric evolution, tectonic and ocean–atmosphere redox state models.

3.2 Baseline petrography and geochemistry

An agreed key ambition of the workshop group was the need to establish an integrated, petrographic and geochemical database(s) to provide textural (i.e. primary versus diagenetic features), depositional (i.e. facies, environment) and compositional (i.e. bulk rock versus cements/groundmass versus diagenetic mineralogical fingerprinting) context for the isotopic and palaeobiological sampling, all within a 4-D stratigraphic framework. In many countries research funding is now awarded on condition of data management plans that aim to ensure that the data produced from the funded research will be archived and, where appropriate, made available to the wider research community, along with the required metadata. Any scientific drilling project that is undertaken will require a defined information and data management plan, including implementation of ICDP's established a drilling information system (DIS) approach. At the workshop there was widespread recognition that these approaches are of great utility for a wide range of data, not only those derived from cores, and the community would be wise to embrace and develop (bespoke) systems for widespread use (i.e. for both core and outcrop derived data). Exciting opportunities exist for developing involvement with burgeoning cyber-infrastructure efforts (e.g. EARTHCUBE – http://earthcube.org/). Although such efforts require significant initial investment from the community, the potential payback in terms of efficiency and ability to handle large multivariate data sets is exciting. The workshop participants agreed that such open-access data archiving was a key component for sharing information that ranged from the basic, such as petrography (textures, cements, diagenetic fabrics, etc.), to the proxy records deduced from isotopic data sets (δ^{13}C, δ^{18}O, $^{87/86}$Sr, δ^{34}S, etc.), to the underpinning geochronology (U-Pb, Re-Os, etc.).

4 The need for scientific drilling to accelerate Neoproterozoic research

Few drilled archives exist for Neoproterozoic Earth system research. Two notable exceptions are Oman (South Oman Salt Basin) and Australia (Centralian Superbasin) and these resulted in benchmark papers on, for example, the study of S isotopes, biospheric evolution, geochronology, micropalaeontology, and even one of the earliest papers on cap carbonates (e.g. Amthor et al., 2003; Bowring et al., 2007; Eyles et al., 2007; Fike and Grotzinger, 2008; Fike et al., 2006; Kennedy, 1996; Lindsay and Leven, 1996; Logan et al., 1995; Pisarevsky et al., 2001; Walter et al., 2000; Willman et al., 2006). This is prime evidence of the value of drill core for obtaining important data and insights.

Elsewhere, progress in understanding the Neoproterozoic Earth system has been based overwhelmingly on the study of surface outcrops. However, many sections across South America, central Africa, Australia and Russia suffer from various combinations of deep weathering, thick soil and vegetation cover, or minimal outcrop, including being buried beneath younger strata. Even in arid localities with exceptional exposures (Namibia, southwestern USA, Adelaide Fold Belt, northern Ethiopia), vertical continuity of outcrop belts is limited owing to scree-cover and recessive weathering of fine-grained intervals (i.e. shales that are of great interest geochemically). This limitation of exposure, combined with a lack of subsurface data, impedes construction of 3-D stratigraphic architectures, and underscores the need for drilling to advance understanding of the Neoproterozoic rock record from both a scientific perspective and enabling accurate assessments of resource potential.

Many geochemical, isotopic and magnetic proxy records are prone to resetting/overprinting by secondary alteration processes, which fosters scepticism about the veracity of those records as time capsules of original depositional conditions. Pristine cores would provide complete rock intervals and minimise the effects of weathering, alteration and surficial contamination, thereby enabling more direct evaluation of diagenetic overprinting and reducing uncertainties about geochemical signals being original or secondary. The workshop highlighted that it was particularly essential to get drill cores for studies that examine fossil biomarkers (Love et al., 2009), and that the technical requirements for obtaining non-contaminated cores are high and will impact the technical drilling requirements for drilling and core archiving. Similar arguments apply to palaeomagnetic studies which would require oriented cores. Having such material to generate proxy records, especially when linked to age models, would be valuable data for assessing the linkages between oceanic oxygenation and the evolution of large mobile animals (including predators) that require high oxygen levels.

An archive consisting of a network of continuous high-quality cores providing rocks as unaltered as possible from surface oxidation and weathering, and that can be correlated accurately and precisely between key locations worldwide, was acknowledged as a critical component to address the questions and research highlighted above. Such an archive will enable strategic, and even repeated, high-resolution sampling (e.g. using XRD core scanners) of pristine samples of the hallmark intervals of environmental change and major perturbations in biogeochemical cycles (see Figs. 1, 2). When such data are integrated with outcrop-based data sets, it will enable building an unrivalled 3- and 4-D framework to test ideas and advance our understanding of this hallmark era in Earth history. Continued integration of both outcrop- and core-based records will be required in order to exploit the inherent strengths of each archive type. Based upon our collective experiences, including involvement with the ICDP (e.g. FAR-DEEP, Melezhik et al., 2013), NASA Astrobiology Institute and Agouron Archaean/Palaeoproterozoic scientific drilling projects (e.g. Schröder et al., 2006), we are certain that a set of archives obtained through continental scientific drilling would play a decisive role in helping achieve these goals.

5 Scientific drilling: a catalyst for enhancing international collaboration

The obvious motivation for undertaking a scientific drilling programme is the opportunity to obtain high-quality archives from key sections that are otherwise inaccessible or compromised by weathering. In our case, there is another major motivation: the opportunity to construct a robust and efficient information infrastructure system into which data are freely and routinely contributed through a worldwide network of internationally collaborating researchers. The data sets of field observations, palaeontology, geochemistry (δ^{13}C, δ^{18}O, δ^{34}S, ^{87}Sr/^{86}Sr as well as various other non-traditional stable isotopes and proxy records), geochronology and palaeomagnetics related to Neoproterozoic research have grown exponentially; these are becoming difficult to manage and manipulate, and the lack of accessible, well-catalogued samples is impeding scientific progress. The workshop created the forum for frank discussions about constructing networks and infrastructure that span beyond a single project. An agreed ambition is to develop information infrastructure(s) which can service the needs of researchers developing and exploiting data from both outcrop and core based studies and, where relevant, build upon related initiatives with overlapping goals (e.g. the EARTHTIME initiative, EARTHCUBE, the Cryogenian and Ediacaran subcommissions of the International Commission on Stratigraphy). In addition to these efforts it was noted that opportunities for advanced training within this community should be developed and exploited at an early stage of any scientific drilling initiative.

6 Where and what to drill?

A potential and embryonic organisational structure was discussed during the workshop, one in which research is organised and managed through working groups that have two discreet but overlapping foci: those that are thematically/methodologically focussed (chronology, palaeobiology, geochemistry, etc.) and those that are time-slice/science focussed (e.g. inception of the Cryogenian, late Ediacaran). A land-based scientific drilling programme is readily tractable for the vast majority of Neoproterozoic successions in that most of the target sections can be recovered with relatively shallow cores (tens to hundreds of metres). This means that the overall objective of the proposed ICDP initiative to obtain global coverage of a ∼ 500 Myr time window is eminently achievable if a sustained effort is made. It needs to be stressed that the objective is well beyond the scope of a single ICDP proposal, rather it will require a sequence of proposals and projects that will collectively span several decades (i.e. akin to IODP). In that spirit, a major effort of the workshop was prioritising and planning prospective drilling sites. Our considerations and deliberations for scientific drilling focused on two key science drivers.

1. What is the research motivation for drilling?
2. Where are the best places to drill to recover records capable of providing new data and advancing our understanding of Neoproterozoic Earth history and resources?

One option discussed was to focus on a single site with a complete enough geological record such that a core would capture numerous key events/intervals. This approach is attractive as the logistics are simpler and has been used to some effect in previous ICDP projects (e.g. FAR-DEEP, Colorado Plateau Drilling Project). However, it is disadvantageous in that it does not allow for assessment of the global versus "local" nature of the events captured and, therefore, may not achieve substantially more than is currently known (except perhaps at a higher resolution and with a stronger primary signal). Consequently, an alternative approach was agreed: to focus on a "time slab" (see below) and carry out drilling in several palaeogeographically disparate (i.e. distinct cratons) but coeval successions. The multi-region approach results in increased logistical complexity but has the distinct advantage that the global expression of events can be assessed in the detail not obtainable from surface outcrops (this approach would be analogous to some of the IODP transect expeditions, e.g. 320/321, Pacific Equatorial Age Transect). Three "time slabs" were identified.

1. *Time slab A – transition into the Cryogenian* (*∼ 900 to ∼ 730 Ma*). This time slab would cover the extended interval preceding the Cryogenian. The scientific motivation would be to obtain the data to inform on the conditions during which Earth transitioned from the stable Mesoproterozoic into the Cryogenian, including the evolutionary trends in microfossils and testing ideas about the links between LIP volcanism, weathering and true polar wander.
2. *Time slab B – base Cryogenian to earliest Ediacaran* (*∼ 730 to ∼ 635 Ma*). This encompasses broadly the

Cryogenian interval with its two major phases of global glaciation, the Sturtian ($\sim$710 to $\sim$660 Ma) and Marinoan ($\sim$645 to $\sim$635 Ma), and intervening interglacial phase. The targeted intervals would include the latter and the strata immediately preceding and post-dating the glaciations, but the thick glacial rocks themselves would not be drilled (Fig. 2).

3. *Time slab C – base Ediacaran to early Cambrian* (*$\sim$635 to $\sim$520 Ma*). This would cover the period from the end of the Marinoan glaciation through to the Cambrian explosion, encompassing the interval of time containing the fossil record of animal evolution and the marked transformation of global biogeochemical systems (i.e. oxygenation).

Key targets identified for initial targeting focussed on time slab C and included those in southern China, Brazil and western Russia to build high-resolution records that can be integrated within a resolved chronostratigraphic framework as each of these regions has demonstrated that it is amenable to radioisotopic dating, thus, enabling the integration of regional records to build a global picture. However, the workshop participants also agreed that this was only the initial step in constructing the backbone for future drilling and integrating records worldwide. As the research and drilling programme develops, it is likely that these time slabs will be further subdivided and individual projects more clearly defined.

7 Beyond a scientific drilling initiative

Whilst bringing a subset of the community together to discuss a plan for scientific drilling, the workshop also provided the forum to discuss the development of efforts that transcend the work based upon drill cores. Integration with outcrop-derived data is critical, as these data will be used to cite and contextualise the core-based records. Outlined above (Sects. 3–5) are the drivers and justifications for scientific drilling of Neoproterozoic strata to overcome the drawbacks imposed by deep weathering and lack of outcrop; in places less compromised by such shortcomings research will continue to focus on outcrop studies. Obviously, cores will not directly enhance study of the taphonomy of Ediacaran macrofossils (which require extensive bedding plane exposures), but they will enable a far more detailed and thorough documentation of the strata encasing those intervals, including high-resolution sampling for proxy data. Furthermore, as per the hydrocarbon industry, a 3-D network of cores will provide the geometric control to undertake basin-scale reconstructions and thereby more fully assess and develop continental margins and their fringing basinal depositional frameworks, tectonic models and their attendant regional to global palaeogeographies, as well as an integrated suite of age models to construct rates of accommodation space genesis and the durations and magnitudes of unconformities from basin to basin.

Not all of the workshop discussion time was taken up with academic research objectives. The research community is well aware of the resource potential of many Neoproterozoic successions, particularly hydrocarbons (Craig et al., 2013), and strata-bound mineral deposits (these are numerous but examples include economic deposits of Au, Zn, Cu, Fe, Mn and P). The great transgressive sequences above the Neoproterozoic glacial deposits are particularly attractive hydrocarbon targets, and the rift basins that formed during the breakup of Rodinia are very rich in sedimentary exhalative mineral deposits. It was discussed how the proposed initiative may interface with industrial partners, such as through efforts that allow for the academic study of cores obtained by private companies. This is a topic that will require further discussion as it has the potential for the development of new synergies.

8 Summary

The workshop was a great success insofar that it initiated discussion and progress towards the development of a scientific drilling research initiative charged with accelerating Neoproterozoic research and identified key locations to focus on for initial drilling efforts. The Neoproterozoic time slice challenges the Earth science community with a hierarchy of questions from the broadly profound – such as why did complex, macroscopic life evolve on this planet some 600 Myr ago, and how likely is it that other Earth-like planets may have experienced the same? – to the more detailed – such as how do different but broadly coeval stratigraphic sections that contain distinctly different proxy records relate to one another, or what was the duration of the Marinoan glacial event? Such first-order questions have been or are being actively addressed; however, these in turn are producing a new set of sophisticated second-order questions, all of which centre on the when, how and why of the biogeochemical conditions and mechanisms that transformed Earth into a planet inhabited by metazoans and oxygenated to the levels required for macroscopic life. Addressing these questions in a timely and efficient manner would benefit from an evolved approach to the required collaborative multidisciplinary research.

It was agreed that a programme of scientific continental drilling for the Neoproterozoic must match in spirit and scope that of the IODP and its key role in advancing understanding of the co-evolution of Cenozoic climate and life. Such a programme will involve multiple drilling projects funded by different sources (e.g. ICDP plus industry, NASA, national research foundations) and engage with as wide a spectrum of the Earth science community as possible, one open to and inclusive of researchers hailing from universities, geological surveys and other national academic agencies/foundations and industry-related research groups. Such an ambitious undertaking will engage the Earth science community for a decade and likely longer. The aim would be to have this proposed programme serve as a catalyst for establishing a worldwide alliance of collaborative, integrated scientific research and data archiving that will carry Neoproterozoic research through the next decade and beyond.

Acknowledgements. We gratefully acknowledge financial support from ICDP and ECORD. We thank Nick Swanson-Hysell and an anonymous reviewer for comments on this workshop report.

Edited by: U. Harms
Reviewed by: N. Swanson-Hysell and one anonymous referee

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Sci. Dril., 19, 27–32, 2015
www.sci-dril.net/19/27/2015/
doi:10.5194/sd-19-27-2015

Scientific Drilling
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IODP workshop: tracking the Tsunamigenic slips across and along the Japan Trench (JTRACK)

J. D. Kirkpatrick[1], M. Strasser[2], S. Kodaira[3], J. Sample[4], J. Mori[5], and S. Saito[6]

[1]Department of Geosciences, Colorado State University, 1482 Campus Delivery, Fort Collins, CO 80523, USA
[2]Geological Institute, ETH Zurich, NO G 46, Sonneggstrasse 5, 8092 Zurich, Switzerland
[3]Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan
[4]School of Earth Sciences and Environmental Sustainability, Northern Arizona University, 602 S Humphreys, Flagstaff, AZ 86011, USA
[5]Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[6]Research and Development Center for Ocean Drilling Science, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, 237-0061, Japan

Correspondence to: J. D. Kirkpatrick (james.kirkpatrick@colostate.edu)

Received: 26 October 2014 – Revised: 7 January 2015 – Accepted: 13 January 2015 – Published: 29 May 2015

1 Introduction

Subduction zones produce the world's largest and most destructive earthquakes. Hazards associated with these events include strong ground shaking and, when the seafloor is displaced by shallow earthquake slip, tsunamis can occur. Among the global efforts to mitigate earthquake hazards, investigations and resources for understanding the causes and effects of tsunamis have been relatively few compared to the many studies of strong earthquake shaking. Yet worldwide over the last decade, nearly a third of the loss of human life from earthquakes is attributed to tsunamis (∼ 247 000 from tsunamis and ∼ 535 000 from earthquake shaking for 2002 to 2012). Understanding the dynamic processes and properties that control earthquake and tsunami occurrence is one of the main themes of the International Ocean Discovery Program Science Plan for 2013–2023.

Mechanical models of subduction zones often include a stable region at shallow depth on the plate boundary interface where earthquake nucleation is inhibited and relative plate motion is accommodated by aseismic slip (e.g., Sholz, 1998; Bilek and Lay, 2002; Wang and Hu, 2006). The 2011 M_w9.0 Tohoku-Oki earthquake challenged these models. Slip during the earthquake was greatest at shallow depth near the trench, with most estimates indicating 50–80 m displacement, the largest ever recorded (Ide et al., 2011; Ito et al., 2011; Lay et al., 2011; Yue and Lay, 2011). Bathymetric surveys before and after the earthquake show that the rupture breached the seafloor (Fujiwara et al., 2011). As a result of the unprecedented shallow slip, the tsunami generated by the event overwhelmed harbor tsunami walls and coastal berms and inundated Honshu, causing thousands of casualties and billions of dollars of damage in northern Japan.

Prior to 2011, the long historical and instrumental records available in Japan led most researchers to anticipate that the largest earthquake that would occur in the region would be about M_w9.0. Previous tsunamigenic earthquakes recorded along the Japan Trench include the 1896 Sanriku and 1677 Enpou Boso earthquakes that occurred on the northern and southern portions of the margin, respectively (Tanioka and Gusman, 2012; Fig. 1). However, the Tohoku-Oki earthquake demonstrated that our relatively short instrumental and historical records are inadequate to fully characterize the complex and multi-scale seismic behavior of subduction zones. For example, the 2011 rupture extended 500 km along the Japan Trench and re-ruptured several regions that had experienced smaller events in the past century. If the 2011 event is representative of general subduction zone behavior, tsunamigenic extreme events with very long recurrence intervals could be characteristic of subduction margins globally.

The Integrated Ocean Drilling Program (IODP) Expedition 343/343T sailed 1 year after the 2011 Tohoku-Oki earthquake to investigate the conditions and processes that facilitated the large, shallow slip (Chester et al., 2013a). During

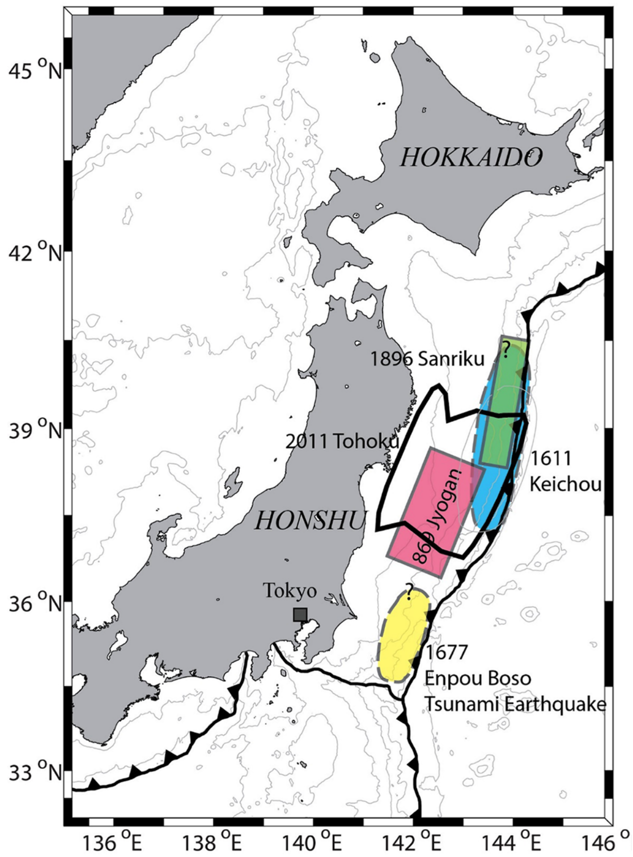

Figure 1. Map of the Japan Trench region showing historical tsunamigenic earthquake rupture areas (Hatori, 2003; Tanioka and Gusman, 2012; Sawai et al., 2012).

Exp. 343/343T, D/V *Chikyu* drilled three holes to around 840 m b.s.f. in a rapid response fault drilling campaign (the Japan Trench Fast Earthquake Drilling – JFAST – project). The success of Exp. 343/343T illustrates that the deep Japan Trench and 2011 earthquake rupture are potential targets for further scientific drilling research, and motivated the pre-proposal Tracking the Tsunamigenic slips Across and Along the Japan Trench (JTRACK): Investigating a new paradigm in tsunamigenic megathrust slip with very deep water drilling using the D/V *Chikyu* (IODP Proposal 835 Pre).

The JTRACK pre-proposal aimed to build upon the results from Exp. 343/343T by targeting the following overarching scientific objectives:

1. Understand the variations of physical and chemical properties of sediments and fluids of the near-trench megathrust that enable huge fault displacements and generate very large tsunamis.

2. Develop and implement new methods for determining the recurrence of giant tsunamigenic earthquakes in the sediment record of the trench fill.

JTRACK was developed to focus on the exceptionally well-instrumented Japan Trench subduction margin where tsunamigenic earthquakes are known to have occurred in 1677, 1896 and 2011 and historical and instrumental records show thirteen *M*7 and five *M*8 earthquakes over the last 400 years, in addition to the 2011 *M*9 event and its aftershock sequence (e.g., Hashimoto et al., 2009; Kanamori et al., 2006). This report summarizes the outcomes of a workshop to discuss the scientific goals of the JTRACK project.

2 Lessons from Expedition 343/343T

During Exp. 343/343T the D/V *Chikyu* penetrated and partially sampled the rupture zone of the 2011 earthquake (Chester et al., 2013a). Drilling in ultra-deep water depths of nearly 7 km, logging while drilling (LWD) data were collected, cores recovered from targeted intervals, and a borehole observatory for long-term monitoring of formation temperatures was installed (Chester et al., 2013a; Taira et al., 2014). LWD data and cores recovered from depths down to ∼ 840 m b.s.f. defined the location and composition of the plate boundary fault (Chester et al., 2013b; Kirkpatrick et al., 2015). Temperature data from the observatory installed during Expedition 343T and recovered 9 months later by R/V *Kairei* showed a thermal anomaly at the megathrust horizon, which was used to infer a very low dynamic friction coefficient of 0.08 (Fulton et al., 2013), consistent with lab measurements of the frictional properties of core samples at seismic slip velocities (Ujiie et al., 2013). These results were made possible by the deep water drilling capabilities of D/V *Chikyu*, and suggest that the resistance to slip on the fault near the trench during the earthquake was minimal.

3 JTRACK workshop goals

The IODP workshop, Tracking the Tsunamigenic slips Across and Along the Japan Trench (JTRACK): Investigating a new paradigm in tsunamigenic megathrust slip with very deep water drilling using the D/V *Chikyu*, was held in Tokyo, 15–17 May 2014. Attended by ∼ 70 scientists from 7 countries and 29 organizations or institutions, the workshop was sponsored by the National Science Foundation U.S. Science Support Program (USSSP), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the European Consortium for Ocean Research Drilling (ECORD). Tokyo was chosen as the location for the workshop because of the proximity to the Japan Trench and to emphasize the ongoing scientific community's response to the devastating 2011 Tohoku-Oki earthquake and tsunami.

The aim of the workshop was to bring together a diverse group of scientists to discuss and develop a plan for scientific drilling in the Japan Trench to establish the seismogenic and tsunamigenic history and potential of the shallow portion of the subduction zone. Building upon the recommendations by the science evaluation panel (SEP) from the JTRACK pre-proposal, the workshop goals were to (1) prioritize the key questions regarding the mechanical behavior of the fault and surrounding rocks, and (2) to develop plans for how to answer those questions with a coordinated program of deep water drilling and complementary giant-piston coring. Following talks that reviewed the instrumental and historical records of earthquakes along the Japan Trench and presented updates on the recent results from Exp. 343, participants worked in breakout groups to address goal (1). Breakout groups were based loosely around the scientific themes of mechanics of faulting, fluid geochemistry and microbiology, borehole logging, long-term monitoring, paleoseismology and geophysical site characterization. Reports from the breakout groups were made and discussed by the workshop as a whole. The breakout groups were then charged with developing strategies for how to address the questions prioritized by the workshop.

4 Recommendations of the workshop

4.1 Deep-sea drilling to investigate the 2011 Tohoku-Oki rupture

Overall, the JTRACK participants agreed that the Japan Trench, and specifically the 2011 Tohoku-Oki rupture are outstanding targets to generally investigate earthquake mechanics and subduction zone processes. The M_w9.0 2011 earthquake presents a unique opportunity to investigate a tsunamigenic earthquake, with results likely to contribute to an improved understanding of the hazard from shallow subduction zone slip along margins globally. Advantages of drilling at the Japan Trench include the extensive pre-existing site characterization information (high-resolution seismic surveys, extensive bathymetric data and planned offshore GPS and OBS (ocean bottom seismometer) deployments), and the success of Expedition 343/343T that demonstrated the viability of drilling in extremely deep water.

The JTRACK pre-proposal included plans to investigate the rupture areas of three known historical tsunamigenic events: the 2011 Tohoku-Oki, 1896 Sanriku and 1677 Enpo Boso earthquakes. One key outcome from the JTRACK workshop was that such an extensive list of drilling targets would be unfeasible for one IODP proposal, and the participants agreed that the highest priority should the 2011 earthquake. The causes of the extraordinary slip near the trench during the 2011 Tohoku-Oki earthquake remain enigmatic, and to build upon results from Expedition 343/343T, it was agreed that the controls on rupture propagation and slip near the trench would be best established by targeting two areas of the rupture, one that underwent very large slip and one where the coseismic slip was relatively small. In combination with high-resolution seismic surveys, this strategy could allow potential lithologic, structural and hydrological controls on slip to be evaluated.

A series of interrelated questions were developed at the workshop that address the physical conditions, material properties and processes that drive shallow slip:

- How does the presence of frictionally weak, velocity-weakening pelagic clay in the incoming plate influence the variable seismic behavior of the plate boundary?
- Is it possible to correlate the seismogenic behavior of the margin with variations in the stratigraphy of the input section?
- Are there differences in fault characteristics in regions that rupture in tsunamigenic earthquakes compared to great earthquakes?
- Are the materials in and around the fault zone capable of storing significant elastic strain between great earthquakes?
- What are the permeability values of rocks in and around the fault zone and how do they contribute to fluid flow and maintenance of fluid pressures and reduction in effective stress in the fault zone?
- Is there proxy evidence for repeated large slip at shallow depths on the plate boundary décollement?
- What is the shear strength and consolidation history of slope sediments and how do they contribute to slope failure during seismic activity?
- How quickly does the plate boundary fault recover and start to build up stress again after a great earthquake?
- How is the recovery process related to the amount of coseismic slip and stress drop?

Pursuing these questions will require acquisition of multiple data sets. The drilling strategy outlined during the workshop includes two transects perpendicular to the Japan Trench at latitudes corresponding to the region of maximum slip of the 2011 Tohoku-Oki earthquake and where the slip was substantially lower. Both transects have three sites (Fig. 2) which include boreholes on the inner trench slope, reference sites on the incoming plate and basin drilling for sediment records (see Sect. 4.2). At the inner trench slope and reference sites, LWD measurements and cores will be used to define the lithology, structure, stress state and mechanical and hydrological properties of the frontal prism, subducted plate and input section. In addition, a long-term borehole observatory to monitor the subsurface pore pressure and temperature field over time is planned at one inner trench slope location. This drilling strategy was designed to enable the work to be carried out in several short-duration expeditions.

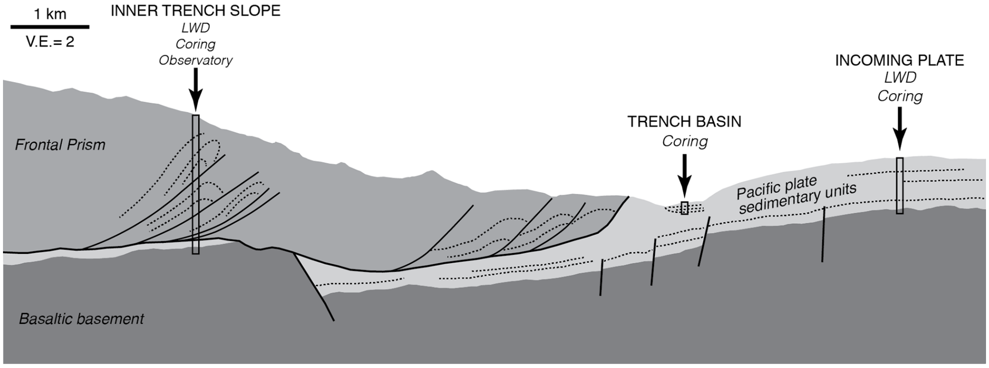

Figure 2. Schematic section through the frontal prism, trench and incoming section showing the framework for the two proposed trench normal transects, locations of the holes and list of target data for each hole (dashed lines represent possible bedding attitudes; solid lines are possible faults; structure based on Nakamura et al., 2013).

4.2 Giant-piston coring to investigate the sedimentary record of earthquakes

Following the SEP recommendation for a staged program, the workshop participants further agreed that addressing JTRACK objective 2 (i.e., develop and implement new methods for determining the recurrence of giant tsunamigenic earthquakes in the sediment record of the trench fill) requires an integrated 4-D approach that captures the sedimentary record of past earthquakes along the entire trench. The Japan Trench was identified by the workshop participants to be an area well predisposed for submarine paleoseismology according to criteria recently discussed in the open literature (i.e., Sumner et al., 2013; Atwater et al., 2014; Goldfinger et al., 2014). Sediment resuspension and redeposition related to the 2011 Tohoku-Oki earthquake has been documented and the respective deposits are preserved in basins formed by flexural bending of the Pacific plate. These basin are promising study areas for testing earthquake triggering of event deposits because the forearc slope is relatively simple, without large canyons, and Pleistocene sedimentation in hadal basins is not significantly affected by eustatic sea level changes. Results from conventional coring covering the last $\sim$1500 years of the trench fill reveal good agreement between the sedimentary record and historically documented earthquakes. Therefore, the potential is high for submarine paleoseismology encompassing longer timescales accessible only by giant-piston coring and drilling.

A multi-platform, multi-coring strategy was developed during the workshop to utilize a combination of long, intermediate and short cores to be recovered from boreholes drilled by D/V *Chikyu*, mission-specific platform (MSP) giant-piston coring and conventional coring, respectively (Fig. 3). JTRACK paleoseismology research objectives are as follows:

I. Identify the sedimentological, physical, chemical, and biogeochemical proxies of event deposits in the sedimentary archive that allow for confident recognition and dating of past earthquakes (conventional & MSP giant-piston coring).

II. Explore the spatial and temporal distributions of such proxies and investigate how they relate to fault characteristics and rupture areas of great earthquakes across the entire Japan Trench subduction system (conventional & MSP giant-piston coring).

III. Elucidate the long-term recurrence pattern of events similar to the 2011 Tohoku-Oki earthquake (D/V *Chikyu* drilling).

The resulting earthquake catalog could be 10–100 times longer than current information on earthquake history. This catalog would help resolve the long-term recurrence pattern of great earthquakes at subduction zone margins, by testing the following two hypotheses:

– Great earthquakes have quasi-periodic recurrence owing to a seismic supercycle as predicted by a simple elastic rebound model.

– Great earthquakes occur randomly in time with a low, but on average, constant probability (Poissonian earthquake model).

5 Outcomes of the workshop

A full proposal for drilling in the Japan Trench was prepared after the workshop and was submitted to IODP in September 2014 (Proposal 835 Full – Japan Trench Tsunamigenesis). In parallel, a pre-proposal for a multi-coring approach by a MSP giant piston along an axis-parallel transect of the Japan Trench was developed following the workshop and was also submitted to IODP in September 2014 (Proposal 866 Pre – Japan Trench Paleoseismology). Further work to investigate other portions of the Japan Trench margin that have caused

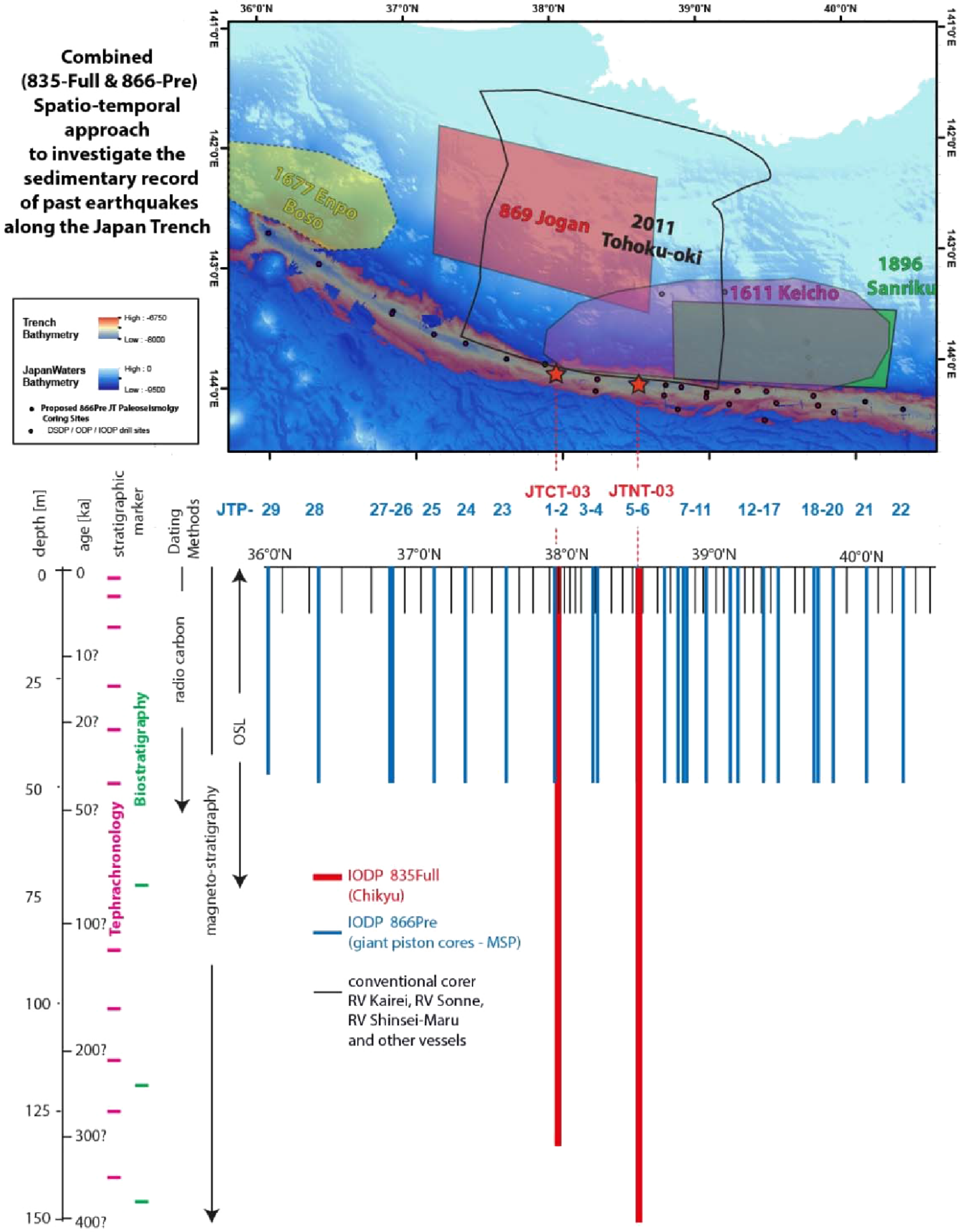

Figure 3. Graphic illustration of the integrated spatiotemporal research approach to investigate the sedimentary record of past earthquakes along the Japan Trench. The figure illustrates the schematic age–depth range (not to scale) and methods to establish absolute (upper part) and relative (lower part) recurrence of extreme event deposits along multiple, trench parallel coring transects by IODP mission-specific platform (MSP) giant-piston coring (JTP-Sites, Proposal 866 Pre) and accompanying short coring campaigns from conventional research vessels.

tsunamis will be planned in future proposals. More details regarding the workshop can be found on the CDex and USSSP websites.

Acknowledgements. We thank JAMSTEC, USSSP, CIB, JDESC and MagellanPlus for generously providing financial support for the JTRACK workshop and the attendees. Thanks also to JAMSTEC for hosting and providing assistance planning the workshop and Lisa McNeill for liaison with SEP and constructive input. We appreciate the constructive feedback from two anonymous reviewers that helped improved this work. Most importantly, thanks to the workshop attendees for their enthusiastic and insightful contributions.

Edited by: T. Wiersberg
Reviewed by: two anonymous referees

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doi:10.5194/sd-19-33-2015

Scientific Drilling
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Drilling through the largest magma chamber on Earth: Bushveld Igneous Complex Drilling Project (BICDP)

R. B. Trumbull[1], L. D. Ashwal[2], S. J. Webb[2], and I. V. Veksler[1]

[1]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[2]School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa

Correspondence to: R. B. Trumbull (robert.trumbull@gfz-potsdam.de)

Received: 1 December 2014 – Revised: 31 March 2015 – Accepted: 13 April 2015 – Published: 29 May 2015

Abstract. A scientific drilling project in the Bushveld Igneous Complex in South Africa has been proposed to contribute to the following scientific topics of the International Continental Drilling Program (ICDP): large igneous provinces and mantle plumes, natural resources, volcanic systems and thermal regimes, and deep life. An interdisciplinary team of researchers from eight countries met in Johannesburg to exchange ideas about the scientific objectives and a drilling strategy to achieve them. The workshop identified drilling targets in each of the three main lobes of the Bushveld Complex, which will integrate existing drill cores with new boreholes to establish permanently curated and accessible reference profiles of the Bushveld Complex. Coordinated studies of this material will address fundamental questions related to the origin and evolution of parental Bushveld magma(s), the magma chamber processes that caused layering and ore formation, and the role of crust vs. mantle in the genesis of Bushveld granites and felsic volcanic units. Other objectives are to study geophysical and geodynamic aspects of the Bushveld intrusion, including crustal stresses and thermal gradient, and to determine the nature of deep groundwater systems and the biology of subsurface microbial communities.

1 Introduction

With on the order of 1 million km^3 of igneous rocks, the Bushveld Igneous Complex is by far the world's largest igneous intrusion, preserving a unique record of magma chamber processes on a truly grand scale. In fact, Bushveld by itself is a large igneous province (LIP) according to criteria of Bryan and Ernst (2008): $> 10^5$ km^3 of magma, mostly mafic in composition but commonly also felsic; and a short (ca. 1 million year) duration of magmatism. The enormous size and rapid emplacement of the Bushveld intrusion poses first-order questions about how vast amounts of magma are generated from the mantle and emplaced in the crust, and what consequences these processes have, both geodynamically and in terms of the palaeo-environment.

The Bushveld Complex is well layered and bimodal in composition, with subequal proportions of mafic (layered ultramafic and mafic cumulate rocks) and felsic units (roof-zone granites and felsic volcanic rocks). This diversity of magma compositions, and the stratigraphic framework provided by its layering, present a rich opportunity to study, in detail, the effects of magma evolution and mixing of melts with diverse mantle and crustal sources. The complex also contains fabulous mineral wealth, with world-class deposits of strategic and precious metals that are vital for both the South African and global economies. Most important of these are the platinum-group metals for which Bushveld alone contains on the order of 70 % of known world reserves, but there are also very important other commodities including Cr and V. All of these ores are orthomagmatic; that is, they are directly related to igneous processes within the intrusion, so their formation cannot be understood without knowing the inner workings of the magma chamber and vice versa. It should be noted that a large part of current understanding on layered intrusions is based on decades of research of the Skaergaard intrusion in Greenland, which is tiny compared to Bushveld (Fig. 1) and appears to represent just one intrusive episode followed by closed-system crystallization. Some features of layering in the Bushveld Complex are similar to Skaergaard, but Bushveld shows evidence for multiple intru-

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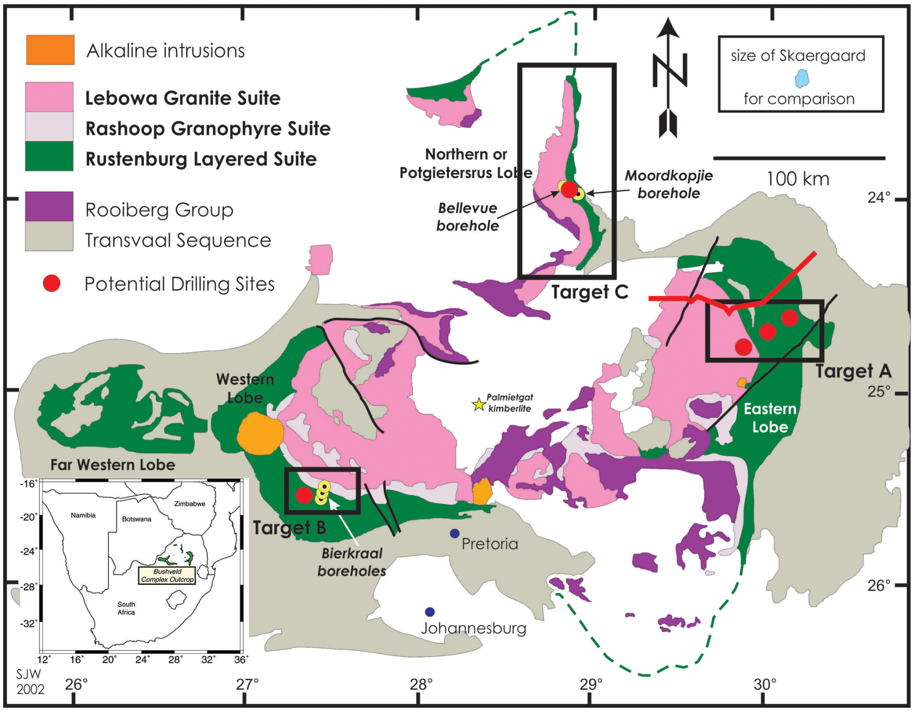

Figure 1. A simplified map of the Bushveld Complex with location of existing boreholes (yellow) and the potential ICDP sites in the western, northern and eastern lobes (red dots in boxes). The inset in upper right shows the size of the iconic Skaergaard layered intrusion for comparison. The thick red line above target A is a reflection seismic line of the Council for Geoscience. The Palmietgat kimberlite in the centre of the complex (star) contains Bushveld xenoliths, confirming geophysical evidence for a continuity of E and W lobes (see text).

Figure 2. Bushveld workshop participants pose in front of the Great Hall at Wits University.

sive pulses and for chemical interaction with the host rocks, which adds layers of complexity to the Skaergaard model.

The motivation for an International Continental Drilling Program (ICDP) project in the Bushveld Complex is to focus and coordinate efforts of the international community towards solving outstanding scientific questions that can best be studied in this world-class location (see below for a list of the main goals). An essential and central part of this project will be to establish permanently curated stratigraphic reference profiles of the Bushveld Complex accessible for future research. But Bushveld is not just a window into Earth processes at depth and in the past, it is also a major socio-economic focus in South Africa. Therefore, issues of land use, hydrogeology, mine safety and public awareness of "geo-issues" are equally part of the equation. And a very important benefit of the ICDP project will be to provide international exposure, research and training opportunities to students and young researchers from all participating countries and from South Africa in particular. Finally, the economic importance of the Bushveld Complex means that the mining and mineral support industries are very active. This is an advantage for the ICDP project because of the local drilling expertise, and also because of industry involvement, with in-kind contributions of data and core materials to the archive, and possibly also with help to offset the drilling costs.

Putting all of these aspects into the framework of an ICDP project proposal was the goal of an international workshop that took place in Johannesburg from 7 to 10 September, 2014, under the sponsorship of ICDP and hosted by the University of the Witwatersrand's School of Geosciences (Fig. 2). The workshop was attended by 55 delegates representing South Africa, Germany, UK, Denmark, Austria, Canada, Australia and the People's Republic of China. In addition to researchers from academia, the workshop attracted participation from South Africa's Council for Geoscience, the Water Research Commission and the mining sector. Six of the participants were postgraduate students engaged in Bushveld-related research.

Because of the importance of debate and discussion, formal presentations were limited to just a few keynote talks giving overviews of the three main discipline groups: igneous petrology and metallogenesis, geophysics and geodynamics, and hydrology and microbiology. The main part of the workshop was devoted to the following tasks:

– formulating the key scientific questions and the role of drilling in answering them;

– exploring synergies among the discipline groups and stakeholders, and any special conditions of drilling needed to accommodate them;

– choosing the best drill site or combination of drill sites to achieve maximum scientific benefits within a realistic scope of logistics and costs;

– establishing working groups and a steering committee to carry the momentum forward to a full drilling proposal.

2 Scientific background and controversies

The Bushveld Igneous Complex includes a mafic/ultramafic layered sequence called the Rustenburg Layered Suite (RLS), which contains the main ore horizons, and two suites of felsic intrusive units above: the Rashoop Granophyres and the Lebowa Granite. The youngest member of the complex is volcanic: the Rooiberg felsic lavas. Controversies exist about the genetic relationship between the felsic and mafic magmas (VanTongeren et al., 2010), as well as about the links of intrusive vs. extrusive magmatic units (Buchanan et al., 2004; Mathez et al., 2013). For example, Walraven (1997) determined an age for the Rooiberg volcanics at 2061 ± 2 Ma (million years ago), which is statistically indistinguishable from U–Pb zircon ages of 2055–2060 Ma obtained from various parts of the Rustenburg Layered Series (Buick et al., 2001; Scoates and Friedman, 2008). Very recent high-precision dating by Zeh et al. (2014) limits the time of emplacement for the entire 8 km thick layered series to less than 1.6 million years, which places important constraints on, and offers new fuel for debates about, the processes of magma generation and evolution, crystallization and layering of the magma chamber, the formation of ore deposits and the post-magmatic effects related to cooling and wall-rock interaction.

The exposed part of the Bushveld Complex is divided into western, northern and eastern lobes (Fig. 1). The arcuate east and west lobes appear to be connected at depth based on gravity models and seismic tomography (Webb et al., 2004; Kgaswane et al., 2012), and this was supported by discovery of layered-series xenoliths brought up in the central Palmietgat kimberlite (Webb et al., 2011; see Fig. 1). Most of the currently mined ore deposits are located in the western and eastern lobes, but the northern lobe also contains important platinum-group element (PGE) deposits (e.g. Platreef) and there is active exploration ongoing. Finally, there are mostly hidden or eroded remnants of the RLS in the far west and in the south (dashed lines on Fig. 1). These parts of the intrusion are surprisingly similar given the great distances between them; however, there are lateral changes in thickness and continuity of some units that have implications for economic geology and have sparked ongoing debates on the sequence of magma-chamber filling and the importance of sedimentary processes like gravity-driven slumping, scouring and crystal slurry transport (e.g. Maier et al., 2013).

3 The need for drilling: goals and benefits of an ICDP project

The Bushveld Complex had been studied geologically even before the discovery of platinum there in 1924, and it continues to attract international research (e.g. 13 ISI publications in 2014). However, partly because of its sheer size and complexity, but also for lack of research coordination and access to drill-core samples, which are mostly held by industry and pertain to only the narrow mineralized intervals, the work has been piecemeal. Most of the 8 km thick layered sequence of the Bushveld Complex is below the surface. Spotty access by mining operations or fortuitous outcrop reveals only parts of the sequence in detail, and without vertical continuity. Understanding how the Bushveld magmas formed, accumulated and crystallized into layers requires studying a continuous vertical sequence including the roof and floor zones. This cannot be achieved from existing drill cores. Furthermore, some of the interesting scientific topics require techniques or conditions such as oriented core, or fluid and biological sampling, which can only be provided by dedicated new drill holes.

The workshop identified the following sets of scientific questions that ICDP should address:

1. Melt origin, melt evolution and magma chamber processes: How many separate melts were involved in filling the Bushveld magma chamber(s) and over what time interval? From where were these melts derived; how much did they mix and how much left the system? How quickly was the complex assembled and how fast did it cool down?

2. Crust–mantle interactions and origin of the Bushveld granitoids: How large is the proportion of mantle vs. crustal material in the mafic and felsic magmas? Are the two magma series related to each other and, if so, how?

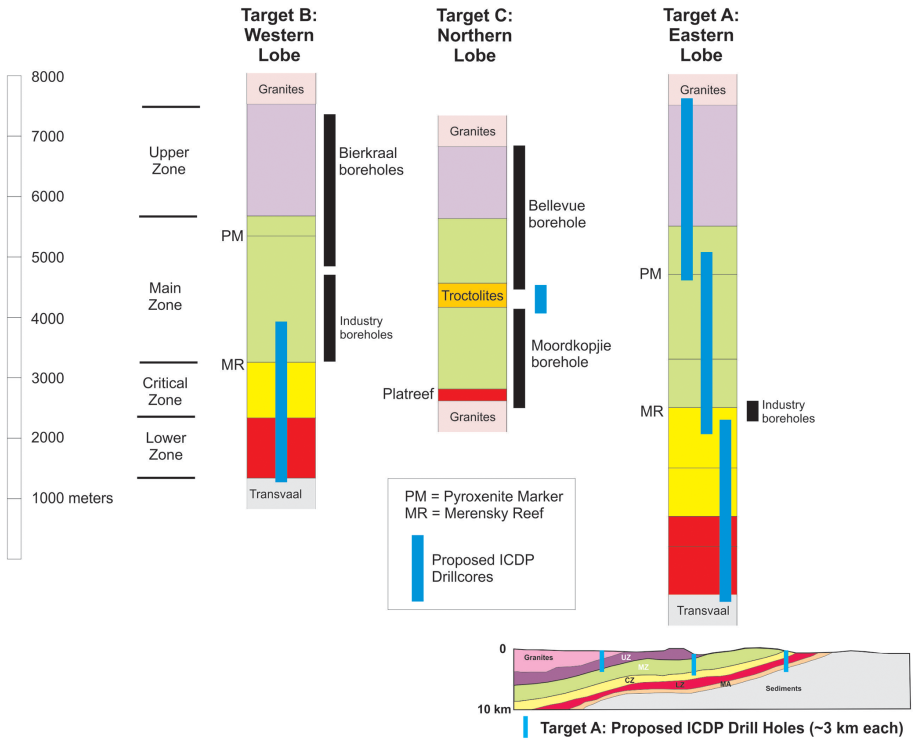

Figure 3. Schematic stratigraphic sections of the Bushveld lobes illustrate ICDP targets A, B and C. The cross section of the eastern lobe (right) explains the staggered-hole concept for target A (see text).

3. Origin of ore deposits: How important were vertical transport processes in the magma through crystal settling and sinking of sulfide melts? What was the role of melt mixing or unmixing in ore formation? How important was lateral transport and reworking of ore zones by hydrothermal fluids?

4. Geophysical properties, geodynamic processes: What isostatic effect did emplacement of the Bushveld magmas have, what are the implications for elastic thickness of the lithosphere? How many magnetic reversals are recorded in the Bushveld mafic section? What is the present state of stress and heat flow in the crust, and their variations with depth?

5. Hydrogeology and the deep biosphere: How is the quantity and quality of deep groundwater in the Bushveld area distributed? What is the effect of mining on these distributions and on hydraulic conductivity? Is there a geothermal potential? What is the nature and productivity of subsurface biomes, what are their energy sources and what role does water–rock interaction play thereby? How old are the deep microbe lineages, and to what extent do near-surface and deep communities interact?

4 Workshop recommendation and follow-up

Consensus was reached early on that the central role of the ICDP project should be to establish internationally available reference sections through the Bushveld Complex on which coordinated research can be focused. There must be permanent curation of the drill cores following ICDP best-practice guidelines, and an ideal host institution for this archive would be the South African Council for Geoscience.

The issue of site selection is a difficult one because of the size of Bushveld and its geographic division into three widely separated lobes, each of which has pros and cons for location of a major drilling project. One of the important site considerations was coverage of part of the stratigraphy from existing cores, and/or availability of deep geophysics and other information to guide drilling. Champions for each of the three lobes presented their cases and there was much discussion. A common concern was that any one "reference section" would necessarily neglect lateral variations, which could be critically important for many of the scientific questions. The recommendation therefore was for a combination of targets that would integrate existing cores and allow constructing profiles for all three lobes at reasonable cost/benefit.

The main effort and expense will be invested in the eastern lobe (Target A, Fig. 1), where no deep holes currently exist, and where drilling can be sited to take advantage of the westward dip of the units. For this target, three holes of

3000 m each, spaced along an E–W traverse across the tilted section, would cover the full 9000 m profile (see Fig. 3). In the western lobe (Target B), existing drill cores (Bierkraal and industry holes) cover the upper section from the roof to mid-intrusion (see Tegner et al., 2006), and it is proposed to continue this downward a further 2500 m into the floor (Fig. 3). For the northern lobe, too (Target C), a full reference profile can be achieved by adding about 500 m to two existing cores (Bellevue, Moordkopjie), which have been described by Ashwal et al. (2005), Roelofse and Ashwal (2012) and Tanner et al. (2014).

The workshop recommendation, therefore, calls for a combined drilling project to obtain about 12 000 m of core, much of it oriented to allow for palaeomagnetic studies. While this is a very ambitious proposal implying substantial investments, we are convinced that it is justified by the benefits of obtaining not one but three archived reference profiles through the world's largest layered intrusion and platinum orebody, which will permit research on both the vertical and lateral variations.

The final achievement of the Bushveld workshop was to appoint a steering committee representing the main scientific groups and all participating countries, as well as several task groups to solve outstanding issues needed in preparation of a full drilling proposal. These include three drill site groups that will collect existing information needed to specify the exact drilling targets, a liaison group to inform and enlist support from industry, community and regulatory agencies in South Africa, and a group to draft plans for outreach and capacity building modules.

Acknowledgements. First thanks goes to all participants for their input to the workshop and to many of them who agreed to take on tasks going forward. The Bushveld workshop was funded by a grant from the ICDP, which is greatly appreciated. The School of Geosciences of the University of the Witwatersrand and its head Roger Gibson were excellent hosts. Special thanks are due to Ulrich Harms of the ICDP Operational Support Group for his buoyant enthusiasm, encouragement and good advice. This workshop report benefitted from constructive reviews by Takashi Hoshide and an anonymous referee.

Edited by: T. Morishita
Reviewed by: T. Hoshide and one anonymous referee

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Sci. Dril., 19, 39–42, 2015
www.sci-dril.net/19/39/2015/
doi:10.5194/sd-19-39-2015

Scientific Drilling
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Workshop Reports

Newfoundland Neogene sediment drifts: transition from the Paleogene greenhouse to the modern icehouse

O. Friedrich[1], R. D. Norris[2], P. A. Wilson[3], B. N. Opdyke[4], and workshop participants

[1]Institute of Earth Sciences, Universität Heidelberg, Im Neuenheimer Feld 234–236, 69120 Heidelberg, Germany
[2]Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0244, USA
[3]National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, Southampton, SO14 3ZH, UK
[4]Research School of Earth Sciences, College of Physical and Mathematical Sciences, The Australian National University, Building 142 Mills Rd, Canberra, ACT 0200, Australia

Correspondence to: O. Friedrich (oliver.friedrich@geow.uni-heidelberg.de)

Received: 28 February 2015 – Revised: 27 April 2015 – Accepted: 5 May 2015 – Published: 29 May 2015

Abstract. This workshop brought together specialists from various fields to develop a drilling proposal to fill the "Oligo-Miocene Gap" that exists in our understanding of the functions of Earth's systems. We propose to establish the first continuous high-deposition record of the Oligo-Miocene through new International Ocean Discovery Program (IODP) drilling in the North Atlantic to allow the development of a continuous Neogene cyclostratigraphy and to enhance our knowledge of Oligo-Miocene ocean–ice–climate dynamics. The workshop was held in Heidelberg from 15 to 17 September 2014 funded by ESF (EARTHTIME EU), NSF, and the ECORD MagellanPlus Workshop Series Program. A total of 24 participants from six different countries (Australia, France, Germany, the Netherlands, United Kingdom, and United States) attended the workshop, including several early career stage researchers. We discussed certain aspects of Cenozoic paleoceanography and paleoclimate and how the gaps in the Oligo-Miocene could be filled using scientific drilling. The ultimate goal of the workshop (to submit a pre-proposal to IODP) was achieved (IODP Proposal 874-pre was submitted 1 October 2014). Our workshop consisted of overview presentations followed by self-selected breakout groups that discussed different topics and produced text and figures for the proposal. Here, we give a short overview of the major topics discussed during the workshop and the scientific goals presented in the resulting IODP pre-proposal.

1 Scientific rational of the workshop

The Oligo-Miocene time interval ($\sim$34 to $\sim$5 Ma) represents a critical phase of Earth's history after development of Antarctic ice sheets but before large-scale glaciation in the Northern Hemisphere (e.g., Zachos et al., 2001, 2008; Pälike et al., 2006). However, well-resolved marine records spanning this time interval from the high northern latitudes are scarce and incomplete, restricting our view of the early transition into glacial climates and ecosystems in the Northern Hemisphere. A key region is the mid-to-high-latitude North Atlantic Ocean, which represents a global "end member" of deep-water overturning and cryosphere evolution, and a sensitive recorder of both terrestrial and marine high-latitude ecosystems. Of interest are the interaction among global temperature, atmospheric $p\mathrm{CO_2}$, deep-water circulation, ice-sheet volume, and ecosystems that all experience state changes in the Oligocene–Miocene interval resulting in the establishment of near-modern Earth systems.

IODP Proposal 874-pre was submitted as a direct outcome of the workshop. In it we propose to drill high-deposition records of the Oligocene–Miocene interval from the same region of deep-sea sediment drifts that was sampled during the highly successful, early Paleogene-focused Expedi-

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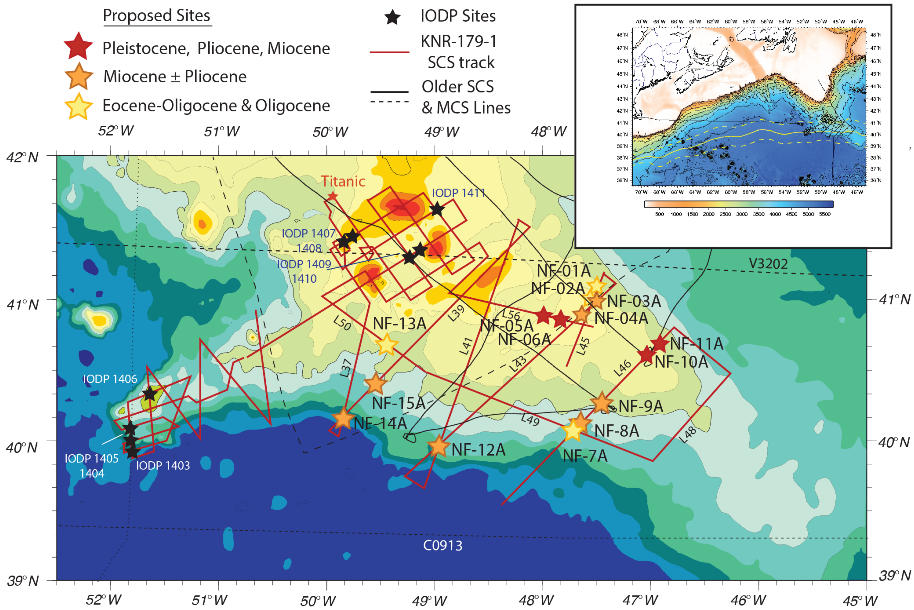

Figure 1. Track map for Newfoundland ridges showing existing SCS and MCS lines and proposed drill sites. Stars of different colors reflect the predominant age for the drilling targets at each site. Black stars are previous Eocene-focused sites drilled during IODP Expedition 342 (Norris et al., 2014).

tion 342 (Fig. 1). That leg targeted sediment drifts of Eocene age on the Newfoundland ridges that proved to have excellent microfossil preservation, magnetostratigraphy, and cyclostratigraphy (Norris et al., 2014). Drilling and the high-quality seismic grid over the Newfoundland ridges reveal the existence of highly expanded Oligocene, Miocene, and Pliocene drift deposits in the region (for an example see Fig. 2). The drifts provide the depth range and temporal record to reconstruct the latest Paleogene–Neogene companion record to Expedition 342's early Paleogene climate history, taking advantage of high sedimentation rates that allow us to obtain very detailed records of Oligocene to Miocene climate events and paleoceanography. New records from the Oligocene and early Miocene can also be linked to Expedition 342's deep-water sites (Norris et al., 2014) to fully reconstruct the North Atlantic carbonate compensation depth.

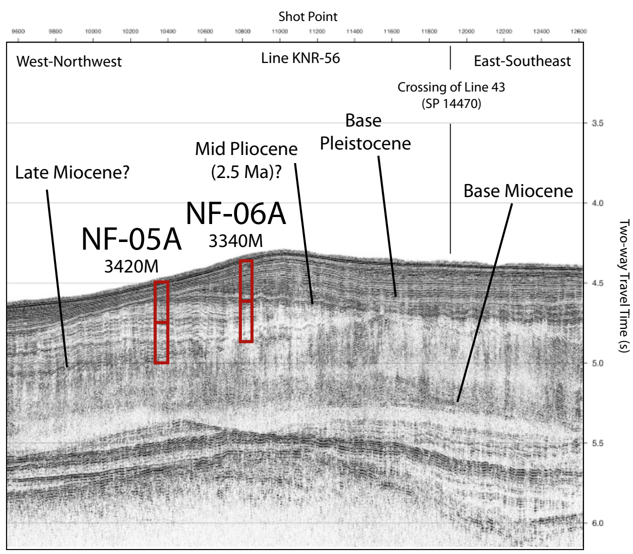

Figure 2. Example of seismic line showing the Miocene drilling target as it appears in seismics at the SE Newfoundland ridges. Two proposed drill sites (NF-05A and NF-06A) are shown for visualization. Red bars indicate a penetration depth of 500 m below sea floor.

2 Discussions during the workshop and direct outcome

The workshop was held from 15 to 17 September 2014 at the Internationales Wissenschaftsforum Heidelberg, Germany. It was the result of various discussions between the convenors and participants in IODP Expedition 342 between 2012 and 2014 that finally led to the organization of the workshop. Having a large amount of information (seismics and stratigraphy) from the foregoing Expedition 342 in the same drilling area, the scientific questions to be answered and potential drill sites could be effectively discussed during the 3-day-long workshop.

The first day was devoted to overview presentations of major scientific themes and questions to set the ground for the following group discussion that took place on the same day. During the discussion, the potential to propose a new IODP expedition to Newfoundland was evaluated. Furthermore, potential links to the existing IODP Proposal 851-

pre (Cenozoic Evolution of the North Atlantic – the Western Atlantic Latitudinal Transect) were discussed because 851 has complementary aims compared to the planned Newfoundland pre-proposal. While the Newfoundland proposal focuses on high-resolution drift sediments from the Oligo-Miocene, proposal 851-pre targets a longer time interval of the Cenozoic but with lower sedimentation rates.

The workshop showed that there is a major, persistent gap in recovery of high-deposition records of Oligocene–Miocene age in the North Atlantic. This gap persists despite the importance of this area and time interval for understanding the evolution of the cryosphere, Northern Hemisphere ecosystem structure, and the history of ocean productivity and chemical balances. Recent drilling in this time interval has focused on the Pacific where new, very highly resolved records with good chronology have been produced (e.g., Holbourn et al., 2013; Tian et al., 2013). A key task is therefore to produce comparable records from the sites of deep ocean overturning in the Atlantic for understanding the relative contributions of regional and global signals preserved in the Pacific records.

Our new pre-proposal focuses on Oligocene–Miocene objectives, particularly the Middle Miocene Climatic Optimum (15–17 Ma). This drilling strategy acknowledges the importance of focusing on extreme climate dynamics (such as the abrupt warming and carbon-cycle dynamics of the middle Miocene).

The participants in the workshop also recognized the value of obtaining both continuous but low-temporal-resolution records from pelagic sites (covered in 851-pre) and high-resolution drift records. The high-resolution record is the target of proposal 874-pre, which was submitted 1 October 2014 as a direct outcome of this workshop. There was also interest in locating one or more sites off West Africa (near Morocco) to obtain a Oligocene–Miocene sediment record with a precession-dominated aridity record, like existing Pliocene records in the Mediterranean. Mediterranean records have proven very useful in adjusting the details of the Pliocene timescale since the aridity record does not require assumptions about orbital tuning of the high-latitude glacial cycle. However, no specific West African drilling target was identified during the meeting. Nonetheless, participants left the meeting agreeing on the importance of drilling off West Africa to extend the orbital timescale back into the early Neogene and update the widely used LR04 stack (Lisiecki and Raymo, 2005) of oxygen isotope records used in the Pliocene timescale.

The following 2 days of the workshop were dedicated to the development of scientific questions and text writing as well as figure drafting for the planned pre-proposal. During this phase of the workshop, analysis of existing seismic data for the SE Newfoundland Ridge (available from previous IODP Expedition 342) was used to identify 15 primary and alternate drill sites that could cover the entire Oligocene–Pliocene sequence with high deposition rate sections. These prospective drill sites also span a ~ 1800 m depth transect, including abyssal sites at up to 5 km water depth. All but three of these sites would be drilled entirely with advanced piston coring (APC) to depths of ~ 250 m.

Immediately following the workshop, on 18 to 19 September 2014, the convenors continued to work on the proposal structure, site forms, cover sheet, and editing text in order to submit an IODP pre-proposal. As a direct outcome of the workshop, IODP Proposal 874-pre was submitted on 1 October 2014 to drill Neogene Newfoundland drift sediments.

3 Future impact of the workshop

Regarding the initial goals, the workshop was highly successful since the outcome was a submitted pre-proposal to IODP (874-pre) and a re-evaluation and revision of an existing pre-proposal (851-pre). For both pre-proposals, text and figures were produced by the participants that can be used by the proponents to submit one or two full proposals to IODP. In the case of 874-pre, the development of a full proposal was recommended by the Science Evaluation Panel based on the evaluation of the proposal in January 2015.

In the event that either of these two expeditions are scheduled by IODP, the workshop will have a great impact on our knowledge of North Atlantic paleoceanography and paleoclimate and will serve as resource for many scientific proposals from the international scientific community. Scientific ocean drilling in the Atlantic Ocean based on these two proposals will massively increase our understanding of the feedbacks and function of Earth's systems through recovery of archives with millennial-scale temporal resolution as well as long-term records. In combination with previous drilling, the planned continuous high-deposition record of the Cenozoic could be used to establish a sophisticated orbital age model for most of the Cenozoic to investigate the spatial and temporal dimension of single events as well as long-term evolution of the Earth's system.

Participants in the workshop

The participants in the workshop (Fig. 3) are in alphabetical order (names in italic: ECRs):

Markus Badger (University of Bristol), *Ian Bailey* (University of Exeter), *Helen Beddow-Twigg* (University of Utrecht), Steven Bohaty (NOCS), *Clara Bolton* (CEREGE), André Bornemann (BGR), *Anja Crocker* (NOCS), Oliver Friedrich (University of Heidelberg), Jens Grützner (AWI), Timothy Herbert (Brown University), Ann Holbourn (University of Kiel), *Pincelli Hull* (Yale University), *Diederick Liebrand* (NOCS), *Peter Lippert* (University of Utah), Lucas Lourens (University of Utrecht), Mitch Lyle (Oregon State University), Richard Norris (Scripps Institution of Oceanography), Bradley Opdyke (ANU), Jörg Pross (University

Figure 3. Group photo of workshop participants in front of the IWH venue. Photo: Lucas Lourens.

of Heidelberg), Yair Rosenthal (Rutgers State University), Phil Sexton (The Open University), *Michael Stärz* (AWI), Thomas Westerhold (MARUM), and Paul Wilson (NOCS).

Acknowledgements. We thank ECORD-ICDP MagellanPlus Workshop Series Program, NSF and ESF (Earthwork EU) for financial support for this workshop and the Internationales Wissenschaftsforum Heidelberg (Ruprecht-Karls-Universität Heidelberg) for hosting the event. All participants in the workshop and proponents of the pre-proposal are thanked for fruitful and successful discussions. Two anonymous reviewers and the editor are thanked for helpful comments and handling the manuscript.

Edited by: G. Camoin
Reviewed by: two anonymous referees

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Sci. Dril., 19, 43–53, 2015
www.sci-dril.net/19/43/2015/
doi:10.5194/sd-19-43-2015

Scientific Drilling
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Workshop to develop deep-life continental scientific drilling projects

T. L. Kieft[1], T. C. Onstott[2], L. Ahonen[3], V. Aloisi[4], F. S. Colwell[5], B. Engelen[6], S. Fendrihan[7], E. Gaidos[8], U. Harms[9], I. Head[10], J. Kallmeyer[11], B. Kiel Reese[12], L.-H. Lin[13], P. E. Long[14], D. P. Moser[16], H. Mills[15], P. Sar[17], D. Schulze-Makuch[18], H. Stan-Lotter[19], D. Wagner[11], P.-L. Wang[20], F. Westall[21], and M. J. Wilkins[22]

[1]Department of Biology, New Mexico Tech, Socorro, NM 87801, USA
[2]Department of Geosciences, Princeton University, Princeton, NJ 08544, USA
[3]Geological Survey of Finland, P.O. Box 96, 02151 Espoo, Finland
[4]Laboratoire d'Océanographie Dynamique et de Climatologie, Université Pierre et Marie Curie, Place Jussieu 4, Case 100, 75252 Paris Cedex 05, France
[5]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
[6]Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, Oldenburg, Germany
[7]Romanian Bioresources Centre, Sector 6, Bucharest, Romania
[8]Dept. of Geology & Geophysics, University of Hawaii at Mānoa, Honolulu, HI 96822, USA
[9]International Scientific Drilling Program, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg C-425, 14473 Potsdam, Germany
[10]Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE17RU, UK
[11]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg C-425, 14473 Potsdam, Germany
[12]Department of Life Sciences, Texas A&M University-Corpus Christi, 6300 Ocean Drive, Unit 5800, Corpus Christi, TX 78412-5800, USA
[13]Department of Geosciences National Taiwan University, Taipei 106, Taiwan
[14]Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[15]Division of Natural Sciences, School of Science and Computer Engineering, University of Houston Clear Lake, Houston, TX 77058, USA
[16]Division of Earth and Ecosystem Sciences, Desert Research Institute, 755 E. Flamingo Road, Las Vegas, NV 89119, USA
[17]Department of Biotechnology, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India
[18]Technical University Berlin, Berlin, Germany, and Washington State University, Pullman, WA 99164, USA
[19]Division of Molecular Biology, University of Salzburg, Hellbrunnerstr. 34, 5020 Salzburg, Austria
[20]Institute of Oceanography, National Taiwan University, Taipei 106, Taiwan
[21]Centre de Biophysique Moléculaire, UPR CNRS 4301, rue Charles Sadron, 45071 Orléans Cedex 2, France
[22]School of Earth Sciences and Department of Microbiology, The Ohio State University, Columbus, OH 43210, USA

Correspondence to: T. L. Kieft (tkieft@nmt.edu)

Received: 2 February 2015 – Revised: 19 March 2015 – Accepted: 23 March 2015 – Published: 29 May 2015

Abstract. The International Continental Scientific Drilling Program (ICDP) has long espoused studies of deep subsurface life, and has targeted fundamental questions regarding subsurface life, including the following: "(1) What is the extent and diversity of deep microbial life and what are the factors limiting it? (2) What are the types of metabolism/carbon/energy sources and the rates of subsurface activity? (3) How is deep microbial life adapted to subsurface conditions? (4) How do subsurface microbial communities affect energy resources? And (5) how does the deep biosphere interact with the geosphere and atmosphere?" (Horsfield et al., 2014) Many ICDP-sponsored drilling projects have included a deep-life component; however, to date, not one project has been driven by deep-life goals, in part because geomicrobiologists have been slow to initiate deep biosphere-driven ICDP projects. Therefore, the Deep Carbon Observatory (DCO) recently partnered with the ICDP to sponsor a workshop with the specific aim of gathering potential proponents for deep-life-driven ICDP projects and ideas for candidate drilling sites. Twenty-two participants from nine countries proposed projects and sites that included compressional and extensional tectonic environments, evaporites, hydrocarbon-rich shales, flood basalts, Precambrian shield rocks, subglacial and subpermafrost environments, active volcano–tectonic systems, megafan deltas, and serpentinizing ultramafic environments. The criteria and requirements for successful ICDP applications were presented. Deep-life-specific technical requirements were discussed and it was concluded that, while these procedures require adequate planning, they are entirely compatible with the sampling needs of other disciplines. As a result of this workshop, one drilling workshop proposal on the Basin and Range Physiographic Province (BRPP) has been submitted to the ICDP, and several other drilling project proponents plan to submit proposals for ICDP-sponsored drilling workshops in 2016.

1 Background: current state of sampling opportunities for deep continental biosphere studies

It has been recognized for decades that deep continental environments contain active, diverse communities of microorganisms functioning in subsurface ecosystems that collectively contain half or more of the Earth's microbial biomass (Whitman et al., 1998). However, despite the global significance of subterranean life, opportunities to study it remain limited. The coring of continental settings for microbiology began in the 1950s, with Russians examining petroleum-bearing sediments. Their goal had been to determine whether the microorganisms discovered by Ginsburg-Karagitscheva (1926), Bastin et al. (1926) and Zobell (1945) in the fluids removed from petroleum reservoirs were indigenous to the formations in which they were found or contaminants from the oil exploration process. Subsequently, drilling for microbes really took off in the mid-1980s with support from the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the U.S. Geological Survey as concerns mounted over the contamination of groundwater by a wide spectrum of pollutants created by the petroleum industry and by the fabrication of nuclear weapons. The success of these drilling programs in identifying indigenous subsurface microbial communities resulted from the pivotal development of tracers for quantifying drilling contamination (Phelps et al., 1989; Colwell et al., 1992; Russell et al., 1992). These pioneering subsurface programs extended the known depth limit of the biosphere, quantified the sizes and activities of subsurface microbial communities, and documented the direct consequences of microbial metabolism on the geochemistry of subsurface environments. Modern molecular biology tools have greatly extended the capabilities for characterizing the phylogeny and metabolic activities of deep subsurface communities. The Deep Sea Drilling Program (now the International Ocean Discovery Program, IODP), which began exploring the subseafloor biosphere in 1990 off the coast of Peru, adopted these tracer technologies for deep-life-driven drilling expeditions in 1999 on Leg 185 (Smith et al., 2000a, b). The first IODP expedition that was designed and carried out with deep life as the primary driver was the Leg 201 drilling of the Peru Margin, the success of which paved the way for subsequent biologically motivated expeditions. The IODP has made exceptional progress over the past 25 years in quantifying marine subsurface microbial abundance, characterizing their diversity, and relating microbial activities to geochemical conditions.

The International Continental Scientific Drilling Program (ICDP) is the continental counterpart to the IODP. Although deep life is a major ICDP theme (Zoback and Emmermann, 1994; Horsfield et al., 2007; Kallmeyer and Kieft, 2014), deep-life studies have so far only piggybacked onto ICDP drilling projects planned for other purposes. To date, no ICDP projects have been conceived and executed with deep life as the primary objective, in part because the deep-life community has been slow to initiate a bio-driven ICDP project. The objective of this Deep Carbon Observatory (DCO)-sponsored workshop, therefore, was to develop one or more deep-life continental drilling projects, which would essentially become the continental equivalent of Leg 201. The workshop was held at the GFZ German Research Center for Geosciences in Potsdam, Germany, on 3 and 4 November in 2014 with support from the DCO and local support from the ICDP. There were 22 participants from nine countries; nineteen of the participants were on site (Fig. 1) and three participated remotely.

2 The deep biosphere

The majority of deep continental subsurface microbes are prokaryotes (bacteria and archaea) living in darkness without

Figure 1. Group photograph of on-site participants of the workshop. From left to right, Heath Mills (USA), Lasse Ahonen (Finland), Bert Engelen (Germany), Phil Long (USA), P.-L. Wang (Taiwan), L.-H. Lin (Taiwan), Jens Kallmeyer (Germany), Eric Gaidos (USA), Sergiu Fendrihan (front, Romania), Dirk Schultz-Makuch (USA/Germany), Duane Moser (USA), Mike Wilkins (USA), Brandi Kiel Reese (USA), Tom Kieft (USA), Uli Harms (Germany), Vanni Aloisis (France), Pinaki Sar (India), T. C. Onstott (USA), Dirk Wagner (Germany) (photo courtesy of Helga Stan-Lotter, Austria).

exposure to photosynthetically generated O_2. In the deepest sites, microorganisms function without access to photosynthetically generated organic carbon, as well; instead, being fueled by hydrogen (H_2) generated from rock–water reactions (Fig. 2) (Stevens and McKinley, 1995; Chapelle et al., 2002; Sleep et al., 2004; Lin et al., 2006; Chivian et al., 2008). A wide diversity of bacteria and archaea has been detected in the continental subsurface, with the majority of these appearing to be indigenous and adapted to subterranean life (Heim, 2011; Colwell and D'Hondt, 2013; Lau et al., 2014). These microbes are active, albeit at slow metabolic rates, and thus are important in the biogeochemical cycling of carbon (Head et al., 2003), nitrogen (Lau et al., 2014), and other biologically relevant, redox-sensitive elements (Pedersen et al., 2008).

Although bacteria and archaea have been the major focus of continental deep-life studies to date, participants with expertise in subseafloor drilling highlighted other biological groups, as well. For example, recent investigations suggest that viruses, including bacteriophages and archaeophages, play an important role in the deep biosphere (Kyle et al., 2008; Eydal et al., 2009). High virus-to-cell ratios found in oligotrophic deep marine sediments indicate ongoing viral production (Engelhardt et al., 2014). Viral lysis might not only control prokaryotic biomass but also release N- and P-rich organic compounds. The integration of this viral shunt into biogeochemical models could modify estimated rates of carbon cycling in the subsurface. Fungi have long been studied in freshwater lakes, soils, surface sediments and, more recently, marine deep subsurface sediments (Nagano et al., 2010; Edgcomb et al., 2011), but are currently not known to be important players in the continental subsurface. In the marine deep subsurface, fungi appear to be reducing nitrate and degrading lignin (Cathrine and Raghukumar, 2009; Gubernatorova and Dolgonosov, 2010), and have been reported in biological samples collected from the deep continental subsurface (Sinclair and Ghiorse, 1989; Reitner et al., 2005). Other eukaryotic components found in the deep continental biosphere include yeasts (Ekendahl et al., 2003), protists (Sinclair and Ghiorse, 1989), and nematodes (Borgonie et al., 2011). Exploration for these ecologically important, but numerically less abundant, members of subsurface ecosystems will require the capability of accessing high volume subsurface material (fluids and/or solids) from any proposed ICDP site.

Most current microbiology-based research efforts that aim to describe subsurface microbial communities utilize so-called next generation sequencing approaches (e.g., Wrighton et al., 2012; Baker and Dick, 2013) that can detect and identify microorganisms present in deep systems even when they comprise $< 1\,\%$ of the total community. Because this technology is sensitive to trace constituents in DNA extracts, maintaining sample quality and conducting proper controls is essential for reducing the likelihood of sequencing contaminants infesting the community database. Methodological and reagent blanks should be included to account for DNA contamination that might occur during sampling and in the laboratory or that might be present in reagents, enzymes, or buffers. By consulting databases that catalog classical contaminant sequences, such as those present in DNA extraction kits (cf. Salter et al., 2014), indigenous minor or rare biosphere microorganisms can be identified with higher confidence. In some cases, oligotyping may differentiate closely related but distinct taxa (McLellan et al., 2013) as well as the respective origin of these taxa (i.e., from the subsurface vs. introduced at some point during the analysis) (cf. Magnabosco et al., 2014).

3 Drilling technology for deep-life projects

Concerns are often expressed by non-biologists that deep-life studies impose onerous methodological costs and constraints. Drilling for microbial investigations does require additional effort to implement quality control and quality assurance (QA/QC) procedures; however, established protocols exist (Kieft et al., 2007; Kieft, 2010, 2015b; Wilkins et al., 2014), and they are compatible with and, in many cases, facilitate the needs of other disciplines, such as biomarker analyses and pore water chemistry. Biological QA/QC involves use of tracers in drilling fluids, subsampling from the center of cores, and quantifying tracers and thus drilling fluid infiltration into the subcores (Fig. 3). Good QA/QC practice

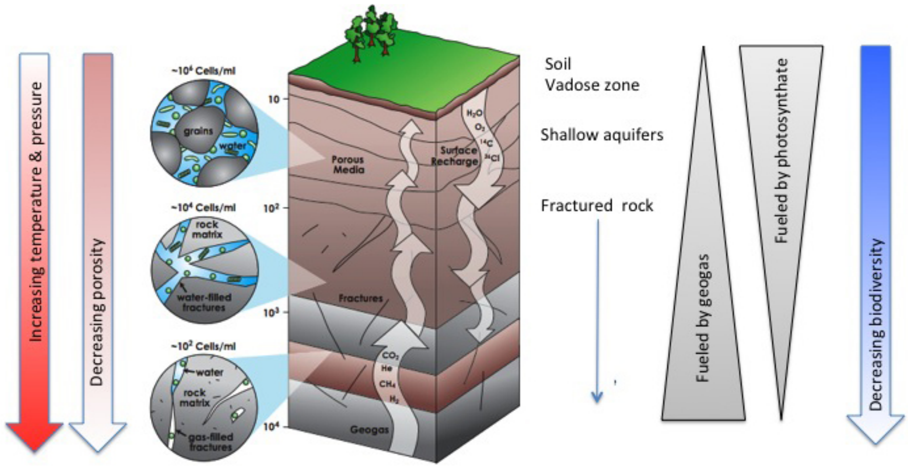

Figure 2. Overview of subsurface continental environments and parameters that typically vary with depth (modified from EarthLab, National Science Foundation, 2003; from Kieft, 2015a).

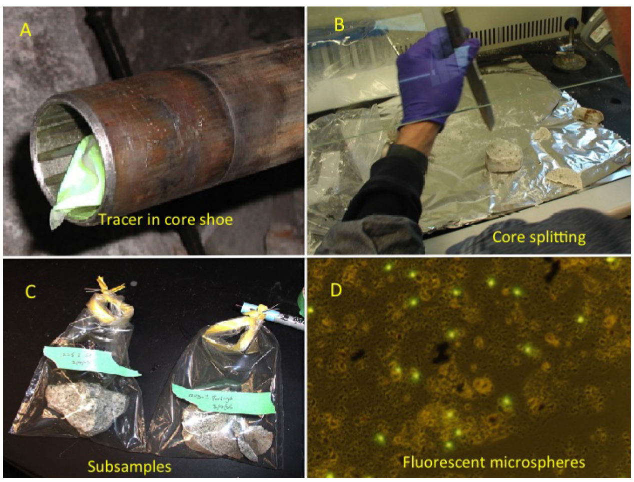

Figure 3. Use of tracers and subcoring for geomicrobiological sampling in a granitic subsurface environment (Sahl et al., 2008). **(a)** Fluorescent microbead tracers deployed in the core shoe, **(b)** subcoring using a hammer and chisel in a laminar flow hood, **(c)** subcore samples in Whirl-Pak® bags, and **(d)** fluorescent microbead tracers in drilling mud, viewed by epifluorescence microscopy.

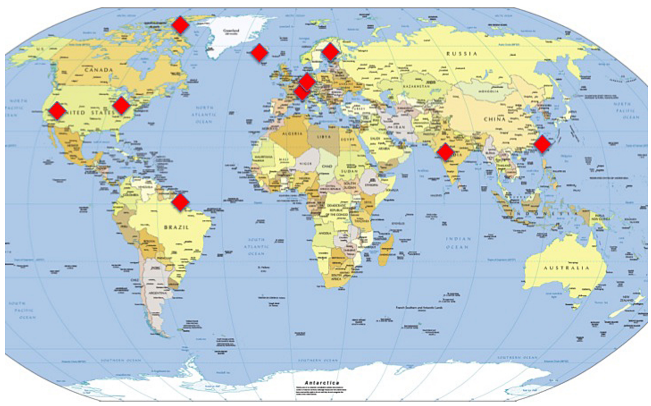

Figure 4. Worldwide locations of drilling sites proposed during the workshop from west to east. (1) Cenozoic Basin and Range Physiographic Province (BRPP), Nevada, USA. (2) Paleozoic Marcellus and Utica shales, Ohio, USA. (3) Mesozoic sediment and salt of Axel Heiberg Island, Nunavut, Canada. (4) Cenozoic Amazon River delta megafan, Brazil. (5) Vatnajökull sub-glacial lakes, Iceland. (6) Cenozoic Eger Continental Rift, Germany–Czech Republic. (7) Cenozoic and Paleozoic salt deposits, circum-Mediterranean. (8) Proterozoic Outokumpu borehole, Finland. (9) Cretaceous–Tertiary Deccan flood basalts, India. (10) Tertiary mud volcano province, Taiwan.

also entails eschewing biodegradable drilling fluid additives, steam cleaning of core barrels, using disinfected plastic inner core liners, and rapidly processing samples on site. New technologies include foam drilling fluids and freezing the core while it is still underground (Kieft, 2015b). Once drilled, the borehole can be completed with packers sealing off discrete layers or fractures and instrumented to measure environmental parameters and biomass at depth. The addition of fluid-sampling and solid sample immersion and extraction would provide for long-term monitoring of and in situ experimentation on the subsurface microbial communities, thereby transforming the borehole into a deep-life observatory.

4 Criteria for drilling projects

The ICDP, International Ocean Discovery Program (IOPD), and DCO have each listed compelling deep-life research questions and, not surprisingly, these lists share many of the same questions. The ICDP asks the following: "(1) What is the extent and diversity of deep microbial life and what are the factors limiting it? (2) What are the types of metabolism/carbon/energy sources and the rates of subsurface activity? (3) How is deep microbial life adapted to subsurface conditions? (4) How do subsurface microbial communities affect energy resources? And (5) how does the deep biosphere interact with the geosphere and atmosphere?" (Kallmeyer and Kieft, 2014). Additionally, the IODP asks how environmental change affects subsurface diversity and ecosystem function (http://www.iodp.org/Science-Plan-for-2013-2023/), and the DCO questions mechanisms of evolution and dispersal and also focuses on microbial transformations of carbon (https://deepcarbon.net).

The continental subsurface is more varied than the marine subsurface in terms of physical and chemical properties, and thus its microbiology is likely correspondingly more varied, as well. Workshop participants discussed developing a systematic approach to the global subsurface biosphere and its biomes, defining them by their physical (T, P), geological (sedimentary vs. igneous), geohydrological (high vs. low connectivity), and geochemical (salinity, low organic C, organic-rich shale, abiotic H_2, etc.) parameters. This discussion of the categorization of globally significant subsurface habitats or biomes led to consideration of which subsurface biomes may have been neglected by previous deep-life investigations. Participants also agreed that the strongest possible deep-life drilling proposals should meet the following list of criteria:

- The proposal should address compelling research questions, as outlined above.
- The proposal should also meet the ICDP selection criteria (http://www.icdp-online.org).
- The 3-D geological structure and the geological history of the proposed site should be understood well enough to formulate ecological hypotheses that can be tested by targeting specific depths or horizons.
- The site should encompass a high diversity of physical, geochemical, and potentially biological attributes.
- The site should have a high probability of possessing active microbial communities.
- The site should have the potential to intersect the depth and temperature limit for life.
- The site should be readily accessible, and should permit long-term access to the completed borehole(s).

5 Proposed projects and sites

Eleven different locations distributed around the world (see Table 1 and Fig. 4) were discussed. Seven of the sites were situated in predominantly sedimentary rock strata, and four sites were located in predominantly igneous–metamorphic rock strata. The geological age of the formations varied from Holocene to Precambrian. Many of the sites either have marine sub-seafloor analogs or provide an opportunity for exploring the continental–marine transition. The sites span the complete range of continental tectonic and hydrogeological settings, some of which have never been explored for subsurface microbial activity. Some of the sites are tectonically active, representing a very dynamic subsurface environment; conversely, other sites represent ancient settings that are tectonically and hydrologically quiescent except for human-induced activity.

5.1 Active continental rift environments

The Eger Rift in Germany hosts a diverse lithology of surficial sediments overlying crystalline rocks, active CO_2 fluxing from the deep crust, and mineral-rich hot springs. An ICDP-supported drilling project called the Probe Intra-continental magmatic activity by drilling the Eger Rift (PIER drilling project) is being planned (Dahm et al., 2013). The main objective of a deep-life component to this drilling project would be to determine how microbial communities respond to variable lithology and fluid fluxes, including CO_2, from deeper strata. Several geological and geophysical studies have already been completed in this area, providing critical background information.

5.2 Active extensional crustal environments

The Basin and Range Physiographic Province (BRPP) covers much of the western United States and represents the largest continental extensional zone in the world. Its hydrogeological characteristics are similar to those of smaller systems, e.g., Rio Grande, East African, Baikal, and Rhine continental rift systems. Extensional systems are characterized by large-scale listric faults, which facilitate the flow of groundwater to great depths and sometimes over tens to hundreds of kilometers laterally. Because the BRPP is located in an arid region, meteoric water recharge in the mountain ranges drives fluid flow towards internally drained or endorheic basins. The surface water ultimately terminates in evaporative sinks, such as the Death Valley Salt Pan in California, where a chronosequence of non-marine salt deposits exist stretching back several hundred thousand years. High geothermal gradients, corresponding with thin crust (e.g., 17–25 km under Death Valley) (Collier, 1990), should enable drilling to the 120 °C isotherm (e.g., the approximate upper temperature limit for known life) at relatively shallow depths. The regional hydrology of this system is well characterized due to U.S. Government studies of groundwater resources and potential contaminant transport from nearby underground nuclear tests. Specific sites for deep-life study in and around Death Valley were proposed based on prior microbiological observations of groundwater transmitted along

Table 1. Proposed drilling projects and sites.

Proposed drill site	Tectonic environment	Geological features	Major scientific questions and themes.
Eger Continental Rift, Germany	Paleogene–Miocene continental rift with active seismicity	Sediments and volcanics	Elevated CO_2 concentrations, seismically induced microbial activity.
Basin and Range Physiographic Province (BRPP), USA	Miocene to currently active crustal extension	Paleozoic limestones in endorheic basin with Pleistocene evaporates and a high geothermal gradient	Temperature limits of life, subsurface microbial transport in carbonate system, microbial survival in young salt deposits.
Ancient evaporites, Austria and Romania	Paleozoic–Miocene marine evaporite sediments	Gypsum to halite and siliclastic interbeds	Salinity limits of life. Sulfate-reducing microbial activity and longevity of microorganisms trapped in mineral fluid inclusions.
Amazon Delta, Brazil	Miocene to currently active continental to marine megafan–delta complex	Rapidly buried, organic-rich, sediments in fresh to saline water	Rates of microbial carbon cycling under rapid burial as a function of salinity. Continental to marine transition.
Mud volcano province, southern Taiwan	Pliocene to active continental oceanic crustal collision	Tertiary sediments actively deformed by thrust faults with fluidized mud and groundwater flow	Microbial communities adaptation to tectonic displacement and pulse heat sterilization generated by fault shearing. Continental to marine transition.
Axel Heiberg Island, Canada	Eocene continental fold and thrust belt	Subpermafrost environment in Paleozoic evaporites	Active sub-zero saline groundwater migration as it relates to subsurface microbial activity, and lower temperature limit for life.
Western Appalachian Basin, USA	Paleozoic organic-rich shale	Hydrocarbon-rich shales/sandstone interfaces	Relationship of organic-rich gradients to microbial activity in a hydrocarbon reservoir.
Deccan Traps, India	Cretaceous–Tertiary flood basalts plus induced active seismicity	Basalts, interbedded sediments overlying Precambrian granite	Multiple mechanisms for abiotic and biotic H_2-fueled microbial ecosystems, seismically induced microbial activity.
Vatnajökull Glacier, Iceland	Tertiary to currently active subaerial oceanic rift zone	Subglacial hydrothermal environment in fractured basalt	Temperature extremes of life. Abiotic H_2-fueled microbial ecosystems in comparison to deep sea vents.
Oman ophiolite, Al Hajar Mountains, Oman	Late Cretaceous oceanic crust obducted onto Precambrian continental crust	Marine ocean crust exposed to meteoric groundwater flow along fractures	Serpentinization leading to abiotic H_2-fueled microbial ecosystems, comparison to subseafloor ocean crust, microbial ecosystems, carbon sequestration.
Fennoscandian shield, Finland	Precambrian metamorphic	Deep saline fracture water in metasediments/metavolcanics/granite	Abiotic H_2-fueled microbial ecosystems.

Figure 5. Possible drilling site near Death Valley, California, on the eastern flank of the Funeral Mountains. A consortium of interests, including the U.S. Department of Energy, U.S. Geological Survey, Inyo County, California, and the Hydrodynamics Group, LLC, drilled a well (BLM-1) to 883 m depth through a range of sedimentary and volcanic lithologies and conducted two hydrologic pump tests. The underlying carbonate aquifer contains anoxic thermal water (58 °C) and abundant sulfate-reducing bacteria including *Candidatus Desulforudis* sp. and *Desulfotomaculum* spp. (Thomas, 2013).

fault zones with known seismic activity (Thomas et al., 2013; Fig. 5). The complex geology creates the potential to examine deep life across conditions ranging from saturated aerobic to anoxic conditions and from mesophilic to hyperthermal temperatures in substrates ranging from ancient evaporites and sedimentary carbonates to young volcanics, sometimes within the same borehole. Characterization of the deep biosphere of this endorheic, continental extensional zone should provide an interesting contrast to that of the oceanic spreading centers.

5.3 Ancient evaporitic basins

Microbiologists have explored the preservation potential of ancient marine salt crystals for trapped microorganisms for decades, but ancient marine evaporitic sequences have never been explored for their deep biosphere potential despite their widespread distribution in space and through geological time. Because of the variety of chemical environments they produce, evaporite deposits have the potential to harbor correspondingly diverse microorganisms (Stan-Lotter and Frendihan, 2011). Gypsum and anhydrite provide a source of oxidants (sulfate and CO_2). A range of interacting extremes (temperature, pressure, salinity) and pore fluid compositions may have selected for phylogenetically diverse deep biosphere communities. Fluid inclusions in halite and gypsum provide refugia where microbes may survive for tens of thousands to millions of years (Mormile et al., 2003). Salt deposits ranging in age from the late Miocene (Mediterranean Salt Giant) to Permian (e.g., Alpine deposits in Austria and Romania) were reviewed as potential candidates for ICDP drilling. The IODP Deep Sea Record of Mediterranean Messinian Events or (DREAM) drilling proposal for the Miocene age evaporites of the Mediterranean provides an opportunity to reveal the secrets of the deep biosphere of subseafloor marine evaporite ecosystems. The primary objective of ICDP drilling into continental evaporite deposits would be to test the long-term survivability of microbes within fluid inclusions.

5.4 Active megafans

Deltaic fans transport continental detrital sediments and terrigenous biota into a marine environment and represent the most rapidly deposited, organic-rich end member of seafloor sediments. Megafans provide opportunities to explore the transition from continental to marine subsurface biomes and to study how organic matter, salinity, and porosity affect microbial composition and function. One megafan discussed was the Amazon delta. Tectonic uplift of the Andes led to a sediment megafan deposited during the last ∼ 5–7 million years. Goals of a combined ICDP–IODP transect would be to document Amazon megafan evolution and to characterize this subsurface biome under continental and marine hydrogeological settings.

5.5 Active oceanic–continental crustal collision environment

In Taiwan, the ongoing arc-continent collision associated with the convergence between the Philippine Sea and Eurasian plates uplifts and exposes Mesozoic metamorphic complexes and Oligocene–Quaternary marine and continental sediments sequentially through a series of thrusts and folds. Such imbricate fault systems influence the compartmentalization of strata, hydrological circulation through discrete units, and channeling of deeply sourced carbon to shallow depths via fluid flow and mud volcanism. The geological context provides unique opportunities to address how microbial communities are shaped by and/or adapted to tectonic displacement of strata, pulse heat sterilization generated by fault shearing, and substrate availability and flux associated with lithological transitions and active faulting. Previous analyses have revealed diverse and active microbial communities present at 1.5 km depth (Wang et al., 2007). At the workshop, the mud volcanoes in southwestern Taiwan were proposed as a potential ICDP–IODP drilling target as they extend along the same fault zone beneath the South China Sea. This tectonic feature provides an ideal setting for studying deep life in a terrestrial–marine transition.

5.6 Subpermafrost environments in ancient fold and thrust belt

Permafrost covers 24 % of the Northern Hemisphere. Contiguous permafrost effectively sequesters the subsurface biosphere from the overlying photosphere and meteorically driven fluid flow. Difficulty in drilling permafrost makes it the least explored of subsurface biomes. The $\sim$650 m thick permafrost on Axel Heiberg Island has chemotrophic bacteria in saline mineral springs sustained by snowmelt recharge through salt diapirs, Mesozoic shale, and sandstone that were structurally deformed in the Eocene (Andersen et al., 2008). This setting provides a unique opportunity to study the effect of fluid flow on the subpermafrost biosphere, while also providing a terrestrial analog for the exploration of life on Mars.

5.7 Black shale interfaces in an ancient foreland basin

Phanerozoic black shale formations are ubiquitous in continental basins and represent important targets for future deep-life studies. The western Appalachian Basin preserves one of the best records of marine black shales, the Ordovician age Utica Shale and Devonian age Marcellus Shale, that were deposited in a foreland basin during the formation of the Appalachian Mountains by arc-continent collisions. The depths of these shale units range from hundreds to thousands of meters. Previous studies of Cretaceous black shales at shallower depths suggest that shale interfaces represent hotspots for microbial heterotrophic activity due to high concentrations of organic substrates that diffuse from the shale into more porous sandstone (Krumholz et al., 1997) and limestone. The heterogeneous nature of the carbon substrate may support diverse microbial metabolisms. Unconventional gas and oil extraction (fracking) adds further interest to this subsurface biome. A major goal will be to compare subsurface microbial diversities and processes between pristine and hydraulically fractured shale interface regions to elucidate the effects of natural gas extraction.

5.8 Ancient continental flood basalts with active seismicity

Continental flood basalts represent another subsurface biome that has only been partially explored in the 15 My old Columbia River Basalt Province (Stevens and McKinley, 1995; Lavalleur and Colwell, 2013). Examining the microbial communities within flood basalts of the 65 Ma Deccan traps was proposed with the goals of gaining a better understanding of (i) H_2-supported ecosystems and (ii) the role of lithotrophic microbes in biogeochemical processes. The seismically active zone of deep basalt, sedimentary interlayers, and underlying Precambrian granite of the Deccan (Koyna-Warna region, India) offers an excellent opportunity to explore three different modes of H_2 generation (i.e., anaerobic oxidation of reduced iron in the basalt, radiolytic production in the granite, and cataclastic production) in one location. An ICDP drilling project to investigate reservoir-triggered earthquakes is already underway and providing some samples for initial microbial characterization (Gupta et al., 2014).

5.9 Active subglacial hydrothermal environments

Iceland's subaerial exposure of the Mid-Atlantic Ridge and its Arctic proximity combine to produce unusual hydrogeology and geochemistry. Volcanic melting of glacial ice maintains lakes beneath the 300 m thick Vatnajökull ice cap and recharges an underlying aquifer in the permeable basaltic crust. The lakes host thriving chemoautotrophic bacteria exploiting volcanic and geothermal sources of sulfur species, CO_2, and H_2 (Gaidos et al., 2009). Goals for ICDP exploration of the subglacial aquifer would be to characterize the microbial diversity, relate microbial metabolism to geochemical energy sources, and probe the lower depth limit of the active biosphere. The site also has direct applications to the search for life in icy worlds, the origin and early evolution of life on Earth, and the potential for carbon sequestration in the mafic crust.

5.10 Ancient ultramafic environments

Ophiolites represent oceanic crust tectonically removed from its marine environment and deposited onto a continental crustal environment where they are exposed to meteoric groundwater. As such, ophiolites comprise an important continental subsurface biome, where serpentinization generates abiotic H_2 and associated CH_4 and high pH, that can be compared to the sub-seafloor biome of oceanic crust. Anaerobic processes include fermentation and sulfur reduction. Ultimately, fluids and near-surface microbes interact with O_2 and CO_2 to consume H_2 and precipitate carbonate. The late Cretaceous Samail Ophiolite site in Oman is ideal for testing hypotheses regarding H_2-fueled chemoautotrophic ecosystems and also carbon sequestration scenarios. The ICDP will soon drill the Samail Ophiolite (Kelemen et al., 2013). However, dedicated geomicrobiology drilling is needed to establish the relationships between the microbial communities, mineral, structure and formation water geochemistry as a function of depth.

5.11 Ancient Precambrian shield environments

The subsurface microbiology of ancient fractured crystalline rocks has been studied for decades and the fractures have been shown to host diverse microbial communities (Pedersen, 1997). The Outokumpu deep drill hole in Finland, which provides access to 2.5 km of Proterozoic mica schist, granite, and serpentinized ophiolite, represents an unusually diverse lithological example of Precambrian shield environments. CH_4, H_2, and N_2 serve as the essential nutrients for life in the deep saline fracture waters (Nyyssönen et al., 2012). Hydrogeological, geochemical and microbiological studies since 2006 indicate high potential for future studies to further test the importance of abiotic H_2 as the energetic driver of subsurface microbial ecosystems.

6 Outcomes

ICDP Executive Secretary Uli Harms advised project proponents on the proposal preparation process, which begins with an ICDP-sponsored drilling workshop proposal. As a result of this workshop, one drilling workshop proposal has been submitted for the BRPP and several other drilling project proponents plan to submit proposals for ICDP-sponsored drilling workshops in 2016. A full drilling proposal was submitted in January 2015 for drilling in the Deccan Traps, India, and this proposal now has a deep-life component that resulted from Pinaki Sar's workshop participation. When funded, these drilling workshops will provide opportunities for continental subsurface deep-life investigators to reach out to the earth science community and to build momentum for deep-life-driven drilling.

Workshop participants

Thomas L. Kieft (co-organizer), Tullis C. Onstott (co-organizer), Lasse Ahonen, Vanni Aloisi, F. S. Colwell, Bert Engelen, Sergiu Fendrihan, Eric Gaidos, Ulrich Harms, Ian Head, Jens Kallmeyer, Brandi Kiel Reese, Li-Hung Lin, Phillip E. Long, Heath Mills, Duane P. Moser, Pinaki Sar, Helga Stan-Lotter, Dirk Schulze-Makuch, Dirk Wagner, Pei-Ling Wang, Frances Westall, and Michael J. Wilkins.

Acknowledgements. We gratefully acknowledge the support of the Sloan Foundation's Deep Carbon Observatory Deep Life Community and of the International Continental Scientific Drilling Program. We thank Jim Fredrickson and an anonymous reviewer for their helpful comments.

Edited by: T. Wiersberg
Reviewed by: J. K. Fredrickson and one anonymous referee

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EGU 2015 General Assembly

The EGU 2015 General Assembly was held 12–17 April, 2015 in Vienna with strong participation of ECORD/IODP and ICDP. The ECORD/IODP-ICDP booth „Scientific Drilling“ served as a platform to discuss running and upcoming scientific drilling projects and opportunities for participation. The ICDP-ECORD/IODP Townhall meeting was held on Wednesday, April 15 and attracted more than 200 attendees. Short presentations on program achievements from Gilbert Camoin (ECORD) and Brian Horsfield (ICDP) were followed by six lightning talks on recently completed or upcoming drilling projects and the opportunity of getting together over refreshments. On the same day, the joint IODP-ICDP session „Achievements and perspectives in scientific ocean and continental drilling“ presented 41 contributions in two oral blocks and a poster block.

Joint AGU-CGU-GAC-MAC Assembly 2015

The joint assembly of the American Geophysical Union (AGU), the Canadian Geophysical Union (CGU), the Geological Association of Canada (GAC), and the Mineralogical Association of Canada (MAC) was held 3–7 May 2015 in Montreal, Canada. With more than 2,000 attendees, the meeting covered the entire Earth and space science spectrum. The interdisciplinary session „Exploring the Subsurface Through Scientific Drilling: Contributions From ICDP and IODP“ reported on recent, ongoing and future IODP and ICDP projects and presented results arising from scientific drilling and new methods applicable to such efforts. IODP Canada and ICDP Canada have organized a joint booth that served as docking station for scientists interested in scientific drilling. Both the session and the booth were very well received by the conference attendees. Support for the exhibition booth was provided by ICDP and ECORD.

Inauguration of the ICDP-GONAF downhole observatory

More than 40 Scientists from seven countries came together for the inauguration of the ICDP GONAF downhole observatory (Geophysical Observatory at the North Anatolian Fault). The workshop was held in combination with the regular GFZ-PBO Turkey meeting on May 20, 2015 in Potsdam.

COSC-1 Sampling Party

The COSC project retrieved drill core from a 2496 m deep borehole in central Sweden to provide detailed insight into mid-Palaeozoic mountain building processes from continent-continent collision, to improve our understanding of the hydrogeological-hydrochemical state and geothermal gradient of the mountain belt and to study the deep biosphere in the metamorphic rocks and crystalline basement (see Lorenz et al., this issue).

A first sampling party was held from 2 to 6 February 2015 at the Core Repository of the Federal Institute for Geosciences and Natural Resources (BGR) where the drill core from the COSC-1 borehole is archived. During the sampling party, 16 scientists from seven countries selected ca. 110 m of drill core for laboratory investigations.

Modern non-destructive techniques such as new and innovative XRF analyses (see Sjöqvist et al., this issue), multi-sensor core logging and optical scanning have been applied to the drill core to provide the sampling party valuable data for sample selection.

MagellanPlus Workshops

The MagellanPlus Workshop Series Programme is designed to support scientists in developing new and innovative science proposals for submission to IODP and ICDP.

Upcoming MagellanPlus Workshop cover topics such as Mantle, Water and Life (June 10–12, 2015, Lyon, France) and Submarine Paleoseismology (July 16–18, 2015, Zürich, Switzerland). Scientists who are interested to take part find more information on the MagellanPlus website http://www.ecord.org/magellanplus.html.

IODP Sessions at AOGS and ICAMG 8

An IODP session focussing on recently achieved expeditions in Asian waters will be held at the 12th Annual Meeting of the Asian Oceania Geosciences Society (AOGS) on 2–7 August in Singapore). Two IODP sessions (S14A-IODP A: Scientific Results from IODP Drilling and Future Scientific Drilling Proposal and S14B-IODP B: Scientific Drilling in the South China Sea to Unravel Continental Breakup and Seafloor Spreading Processes) were organized by IODP Korea for the 8th International Conference on Asian Marine Geology (ICAMG 8) 5–10 October in Jeju Island.

Schedules

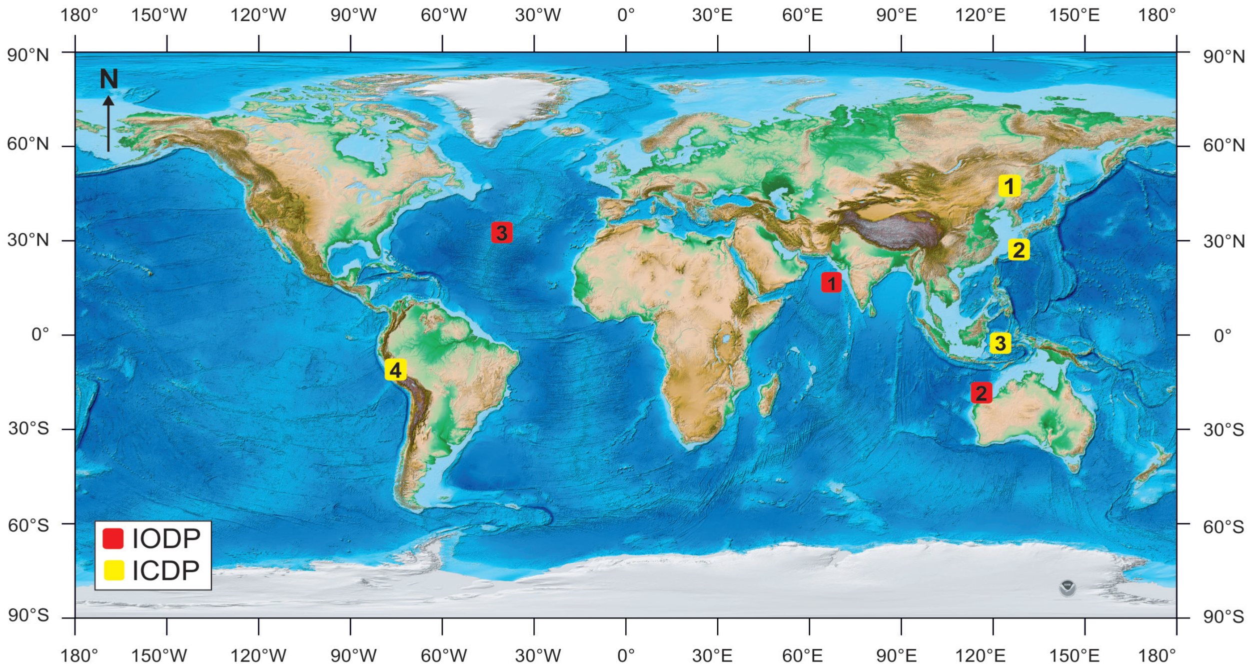
IODP – Expedition schedule http://www.iodp.org/expeditions/

USIO operations	Platform	Dates	Port of origin
1 355 Arabian Sea Monsoon	JOIDES Resolution	31 Mar–31 May 2015	Columbo, Sri Lanka
2 356 Indonesian Throughflow	JOIDES Resolution	31 Jul–30 Sep 2015	Fremantle, Australia
3 357 Atlantis Massif	MSP	24 Oct–9 Dec 2015	To be determined

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

ICDP project	Drilling dates	Location
1 Songliao Basin	Apr–Dec 2016	Songliao Basin, China
2 COREF	Apr–May 2015	Ryukyu Islands, Japan
3 Lake Towuti	May–Jun 2015	South Sulavesi, Indonesia
4 Lake Junin	Jul–Aug 2015	Lake Junin, Peru

Locations



Topographic/Bathymetric world map with courtesy from NOAA (Amante, C. and B.W. Eakins, 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M).

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